THE JOURNAL OF AGRICULTURAL SCIENCE

VOLUME XVIII 1928

CAMBRIDGE
AT THE UNIVERSITY PRESS
1928

PRINTED IN GREAT BRITAIN

CONTENTS

PART 1 (JANUARY 1928)

PART 2 (APRIL 1928)

PART 4 (OCTOBER 1928)

VOLUME XVIII JANUARY, 1928 PART I

INVESTIGATIONS ON YIELD IN THE CEREALS.

IV. THE ACTION OF THE SEED DRILL.

BY F. L. ENGLEDOW, M.A.
Plant Breeding Institute, School of Agriculture, Cambridge.

(With Seven Diagrams.)

CONTENTS.

§ I. INTRODUCTION.

REGULAR distribution, or inter-plant interval, is desirable in all crops. There is, no doubt, an optimum interval for every crop. It must vary with season, soil, variety and other circumstances. While practice cannot, with most crops, attempt to impose an optimum distribution with any great precision, regularity and reasonable limits of density are not impracticable ideals. Gaps in a laid-out orchard are at once apparent as is the fact that for every missing tree the actual yield falls more or less proportionately below the potential maximum set by the soil and other factors. In root crops "misses" and large "gaps" are admittedly definite limitations to yield. Their importance in typical field crops is to be gauged only by precise inquiry. Preliminary investigations have suggested that 10–20 per cent. of the potential crop may be lost in mangolds by gaps and irregularities typical of average fields. Crops like corn and pulses which are drilled and not subsequently spaced by singling, have attracted little attention from the population-density standpoint. Where the "plant" is clearly "thin" a poor crop is usually anticipated. If it is noticeably but not markedly thin, the crop, especially with winter corn, is expected to "gather." That is to say, the unusually great average inter-plant interval is supposed to result in such an

increase of tillering as will "compensate" for paucity of plants. This general principle has a significance in field crops but one which cannot be assessed without full knowledge. It is essential to ascertain first the nature and degree of the irregularities of plant density in representative field crops. Then the spacing-tillering-yield relationship must be determined.

The need for such an ascertainment, suggested by the considerations here outlined, was reinforced by experimental circumstances. In small scale yield trials and studies of cereal plant development, a spacing of 6″ × 2″ is very convenient. Results from plot experiments always stand limited by the fact that they do not necessarily apply to field conditions. Of the many sharp differences between the field and the small hand-sown plot, inter-plant spacing is one of the most patent. To introduce the spatial interval of field crops into plot work it is clearly necessary first to study spacing in field crops. Thus on two widely different grounds the nature and range of plant density in field crops assumes a clear importance.

A first impression of spatial fluctuations may readily be obtained in any field of corn. Successive foot-lengths may be marked out on one or more of the drill rows and the plants in every foot be counted. Next to a foot with 3 plants may be one with 12: then 7, then 21 may follow and so on. For a succession of 50 foot-lengths the mean may be 13 and the limits 1–33. These simple counts may be made at any time between germination and harvest: before tillering has become profuse is the best time.

The mean value and fluctuation of plant density in field crops is a threefold question. The seed rate employed is ordinarily the major determiner of mean value. Large gaps in the rows of plants may be brought about by various accidental circumstances. But the third aspect is the one of most general significance. It is the very localised fluctuation in plant density from point to point along every row of plants. To appreciate the significance of this an acre of corn must be, as it were, differentiated into very small component elements or plotlets. For convenience of discussion the element may be taken as a one-foot length of the drill row of plants. As later explained this length is experimentally and statistically acceptable. Yield per acre is then the sum of the yields from all the elements (there are 65,340 foot-lengths in an acre of corn drilled at 8 in. between the rows, *i.e.* a length of 12·7 miles). To understand how fluctuations in plant density affect yield per acre it is necessary to find out the frequency distribution of plants per foot and the tillering and yield associated with the gradations of plant density.

Procedure for a "census" or count of the plants on an acre, foot by foot, has been described in an earlier paper (1). One hundred samples, each a foot-length of drill row, suitably dispersed, were found to be representative of an acre of corn. Periodic counts were made from germination to harvest for number of plants and for tillering. The harvested produce was counted and weighed. The general result may be illustrated from a crop of Little Joss wheat which averaged 50 bushels of head-corn over 10 acres. At harvest the average number of plants per foot was 11·2 and of ears per plant 1·85. The limits of range for these quantities were respectively 0–24 and 1–7 (all grain-bearing ears, however small, were included). Fluctuation in plant density may be simply displayed by giving the approximate quintiles (equal one-fifth parts) of the frequency distribution of number of plants per foot. These, with the attributes associated with them are contained in Table I (quoted from an earlier paper (1)). Certain features stand out in this

Table I. *For a 50 bushel crop of Little Joss: the quintiles of plant density and certain attributes associated with them.*

Quintile limits (for frequency distribution of number of plants per foot)	0–8	9–10	11–12	13–16	17–24
Average number of ears per plant	2·53	2·04	1·91	1·83	1·31
Average number of ears per foot-length of drill row	15·1	19 3	21·9	26 8	24·5
Average weight of a single ear (gm.)	1·20	1·19	1·18	1·18	1·16
Corresponding rate of yield (bushels per acre)	35 5	45·5	51·0	62·0	56·0

table. The familiar increase in tillering which accompanies diminished plant density is found here. But the values of number of ears per foot-length of row show that increased tillering has by no means "compensated" for paucity of plants. And since average ear-weight (threshed grain) is but little affected by spacing, yield per foot shows a strong association with number of plants per foot. Inferences from absolute values are not warranted. It must not be deduced that a uniform population of 13–16 plants per foot would have raised the yield per acre to 62 bushels instead of 50. And no serious attention should be given to the difference in rate of yield between the fourth and fifth quintiles. But that at least two-fifths of the acre (first and second quintiles) were underpopulated and yielded at a significantly lower rate in consequence, seems a fair inference. In a later experiment on barley (2) at the Norfolk Agricultural Station, by use of the method described in (1), even more emphatic evidence on this general principle was established in two successive years.

The failure of increased tillering, in aggregates of localised thin populations, to compensate for plant deficiency found some explanation in the periodic counts. In wheat some 60 per cent. of the seedling plants survived to harvest: in barley about 80 per cent. Of the tillers existing in the wheat in May, only 40 per cent. produced ears; the rest died. Rate of tiller survival at harvest was higher among thinly spaced plants than in aggregates of denser population. But a countervailing circumstance was the diminution of ear size among the successive tillers of the single plant. Thus, for instance, the fourth and fifth ears of a well-developed plant, forming on tillers that arose late on in growth, were very small and somewhat immature at harvest.

Published results ((1) and (2)) reinforced by subsequent investigations suggest that in irregularity of plant distribution is to be found an important limitation to the yield of typical field crops. For further test and fuller interpretation of this conclusion a wide series of investigations has been undertaken. These have made one conclusion certain—typical corn crops are characterised by marked localised fluctuations in density. While the effects of such fluctuations on yield must be re-examined, it has become necessary to conduct subsidiary investigations into their causes.

Broadly, these causes may be attributed to four influences: (1) the drill, (2) tilth and general husbandry, (3) survival rate of seed, (4) pests, diseases, and other damage. Estimates of actual damage, as of *Helminthosporium* species or Wheat Bulb Fly, are greatly needed for a full interpretation of the limitations to national cereal yield. A form of "census" might prove adapted to such an estimation. The studies here recorded bear upon (1) and (2) and afford a measure of their conjoint and their separate influences.

§ II. Experimental Evidence on Distribution of Seed by the Drill.

Singularly few trials and no analytical experiments appear to have been made upon this complex and important question. The Royal Agricultural Society of England held trials at the Royal Show in 1912. In publishing the results (3) it was stated, "The last trials of Corn and Seed Drills organised by the Royal Agricultural Society of England took place near Bedford in 1874—thirty-eight years ago. It was therefore with considerable interest and some curiosity that agriculturists and implement makers looked forward to the trials of 1912, in the hope that as marked a development might be demonstrated between the prize

drills of 1874 and 1912 as was the case between the first recorded drill invented by Jethro Tull on his farm near Wallingford about the year 1700, and the prize implements of 1874. Anything like such a development was not, however, forthcoming. Indeed, the trials of the machines disclosed that very little alteration or improvement of real importance had been made, and that the prize drill of 1874 very closely resembles the prize drill of 1912."

Four cardinal questions call for discussion in connection with drill action. These are:

(i) The capacity of a drill to deposit seed at specified per-acre rates.
(ii) Rates of sowing of the separate coulters of any one drill.
(iii) Regularity of sowing from point to point along the row marked by any one coulter.
(iv) Interplay of tilth and drill action.

To these must eventually be added others. Labour requirements of steerage and non-steerage drills; effect of wear and tear upon regularity of action; the merits of the chief types of drill mechanism; various adjustments, especially for depth of sowing; cost of production; these are all matters of importance. For the present only the first three cardinal questions are to be considered.

So far as is known the latest published comprehensive evidence as to capacity to sow at specified per-acre rates is embodied in the 1912 trials already mentioned (*vide* (3)). Competing drills were set to sow a well-dressed sample of barley on a carefully prepared barley tilth. A rate of 3 bushels per acre was specified. This, on the test-area, corresponded to a weight of about 4 stone of seed. The weights actually deposited by the eight competing drills were as follows: 3 st. 1¼ lb.; 3 st. 2¼ lb.; 3 st. 7 lb.; 3 st. 7 lb.; 3 st. 9¼ lb.; 4 st. 0 lb.; 4 st. 2¾ lb.; 4 st. 6¾ lb. There was thus a tendency to sow below specification and two of the drills had a deficiency of the order of 20–25 per cent. Having in mind the excellent conditions and the circumstance of competition, it seems fair to conclude that the first cardinal principle of drill action has not been generally secured. Inter-varietal differences in certain crop plants—notably in oats—add greatly to the importance of this principle. A given weight of seed may represent for such an oat as Golden Rain a far greater number of seeds than for Abundance (it may be, in the ratio 125 : 100). Consequently a specified weight of seed per acre gives a far denser plant population for the one variety than the other. Even in wheat fairly accurate adjustment of seed rate for varying circumstances is sometimes desirable. In this first aspect, then, the modern drill which

appears not generally superior to the models of 1912, must be judged not entirely satisfactory. Experimentally, where precise comparisons of varietal yield have to be made, number of seeds sown is a point of importance (*vide* (4), p. 23).

Next is the question of relative rates of deposition by individual coulters of the same drill. In the 1912 trials, as in many subsequent private tests, the procedure was to tie a bag over every coulter and drive the drill a given distance. With a setting for 3 bushels per acre of peas the drills were driven 200 yards. The highest and lowest deposits by individual coulters were:

No. of coulters in drill	Highest and lowest coulters (in lb.)
13	$1\frac{7}{8}$–$1\frac{1}{4}$
12	$1\frac{1}{4}$–1
11	$2\frac{1}{2}$–$1\frac{3}{4}$
12	$1\frac{5}{8}$–$1\frac{1}{4}$
13	$1\frac{5}{8}$–$1\frac{1}{4}$
13	$1\frac{3}{4}$–$1\frac{1}{2}$
13	Choked
13	$1\frac{3}{4}$–$1\frac{1}{4}$

The conditions were not practical farming conditions. Apart from excellence of tilth, the coulters were not actually in the soil. From this trial, then, it seems evident that the coulters on some representative drills, working under very favourable conditions, do not deposit seed at by any means the same rate. The importance of the defect is evident. Further experiment is urgently needed. Its form and scope require careful consideration. Data given in § III (*infra*) make clear that the per-foot deposition of seed is highly fluctuating. In consequence of this "samples" drawn in tests of inter-coulter differences should be fairly large and sufficiently numerous to ensure high statistical probability. There should be, in addition to trials of the kind described, tests of seed deposition on a range of representative tilths.

Regularity from point to point along the coulter row—the third cardinal aspect of drill action—is experimentally the most difficult. With some expense, but without great difficulty, a mechanical test analogous to the bag-test for coulter average deposition, could be devised. Some simple tests of this kind are described in § VII (*infra*). An alternative and more comprehensive test is by actual counts of seeds deposited in the field. Such counts can be made with considerable accuracy—though they are arduous—on any fairly good corn tilth. On a very crumbly tilth it is impossible to be sure of finding every seed. Two checks upon seed counts are possible. Accurate determination of 1000-corn weight and of the total weight of seed deposited on a measured

area give the mean number of seeds sown per foot of coulter row. The mean number actually counted should agree with this. Again, with the very high germination characteristic of good samples of seed corn, counts of numbers of seedling plants should conform with seed counts provided birds and other agencies of damage are excluded. A succession of plant counts must be made, for the total period of emergence of seedlings from the soil may be several weeks. Not only mean values but also dispersion (as coefficient of variation) may be used to check the conformity of seed and plant counts.

The experimental evidence consists of a considerable series of census counts. Some of these (described in (1) and (2)) included plant counts only; in later ones both seed and plant counts were made. General checks were carried out by 1000-corn weight in a number of cases. A full account of the principle of census counts has already been published (1). This principle was employed in all the experiments to be described, the form of application being selected to suit the number of coulters on the drill and other circumstances.

Distribution per foot naturally fails to disclose the full measure of irregularity. Twelve plants in a foot may be uniformly spaced at one per inch; or the whole may be clustered in the first two inches leaving ten inches vacant and so on. Plant development would be very different in these two distributions. It therefore became necessary to determine deposition per inch. The method employed and the data are described in § IV (*infra*) and the analytical considerations which arise, in § V.

§ III. THE PER-FOOT DISTRIBUTION.

In 1926–7 comprehensive census investigations were made on four fields (D, G, L and P) in Cambridgeshire. The purpose was a full analysis of the influence upon yield per acre attributable to fluctuations in plant density. These fields were chosen as offering a range of soil and of level of husbandry. Seed counts were made immediately behind the drill on one-foot samples of drill row, the dispersion and number of samples being as given in the notes on the fields which follow. Periodic plant counts also, were made. In these and in some seed counts, every sample was duplicated. That is to say, at every sample point two adjacent one-foot lengths were observed. The two feet of such a pair are designated α and β. For plant counts the samples were permanent through all counts, their positions being marked by small pegs. Three-inch pegs, inserted to protrude about an inch from the surface, are rarely disturbed by harrowing and rolling. Duplicate samples afford, as later

explained, both a general statistical check on reliability and certain analytical evidences. Dispersion of plant count samples over the selected acre was always such as to give approximately the same number of samples from the work of every coulter of the drill. The acre was chosen so as to represent, as far as judgment could decide, the general conditions of the whole field. For plant counts samples were drawn from 100 points (single or duplicate) per acre.

Field D.

Soil, a clay intermixed with gravel, some 3 ft. deep, and on a gravel sub-soil; in good heart and well cultivated; sowing on Nov. 12 on an excellent wheat seed-bed, firm below and suitably fine on top; an 8-coulter cup drill in good working order was used; Yeoman wheat sown at an intended rate of 2½ bushels per acre; an excellent sample of seed; the seed steeped in formalin and held over for four days on account of bad weather; as later explained, actual germination in the soil was low, owing, it is believed, to delay in sowing after steeping in formalin.

In the seed count 17 duplicate samples were included, a total of 342 foot-lengths. Sample dispersion was such as to give 21 or 22 duplicate samples from the work of every coulter. The general results were:

M	= average number of seeds per foot		= 17·67
M_α	= ,, ,,	α-ft.	= 17·52
M_β	= ,, ,,	β-ft.	= 17·82
σ_α	= standard deviation for α-distribution		= 7·1
σ_β	= ,,	β-distribution	= 6·0

Frequency distribution for combined α and β ft. = Table II D.

Table II shows that the number of seeds per foot fluctuated from 3 to 40, the distribution being of the chance or normal form. The means for α and β aggregates are in close agreement. This agreement is evidence of general reliability of result or representativeness of sampling, provided α and β values be not highly correlated. Now calculation showed that the correlation (denoted by $r_{\alpha.\beta}$) was extremely low and, though based upon 171 entries, not significant in terms of its own probable error. That the sampling was satisfactory may therefore be inferred. The significance of the low value of $r_{\alpha.\beta}$ with reference to drill action is discussed in § V (*infra*). A quick appreciation of the per-foot fluctuation is afforded by the quintiles of the distribution. These, denoted by Q. 1–Q. 5 are approximately:

Q. 1 = 3·0–12·2; Q. 2 = 12·2–15·6; Q. 3 = 15·6–18·1;
Q. 4 = 18·1–21·9; Q. 5 = 21·9–40.

Assuming the representativeness of the sampling, facts in evidence of which have been given, it may be stated that in aggregate the acre consists of five equal parts on which the widely differing seed rates are as shown by the values of Q. 1–Q. 5.

Table II. *The frequency distribution of number of seeds per foot on the four fields.*

	Number of seeds per foot														
Field	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	
D	.	.	.	1	.	2	4	3	9	9	7	11	19	17	
G	.	.	1		2	1	2	6	2	2	14	5	9	8	
L	.	.	.	.		3	2	2	3	7	12	9	15	19	
P	6	2	2	6	1	4	5	7	7	11	12	7	12	9	
	Number of seeds per foot														
Field	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	
D	13	27	26	25	30	18	25	11	18	12	10	11	7	2	
G	22	14	13	6	8	12	15	10	12	6	8	3	3	1	
L	18	23	24	14	21	19	6	13	15	12	9	12	8	5	
P	10	9	5	9	3	5	7	1	.	3	4	2	.	.	
	Number of seeds per foot														
Field	*28*	*29*	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*	*39*	*40*	Total feet	
D	5	4	9	1	3	1	.	.	.	1	.	.	1	342	
G	2	2	.	1	.	.	.	.	.	.	.	.	.	190	
L	4	3	1	1	3	1	1	.	.	.	.	1	.	286	
P		.	.	.	.	.	.	.	.	.	.	.	.	149	

As already explained, the number of plants found when emergence from the soil (*i.e.* effective germination) is complete, affords a check on seed counts provided there has been no damage. On this field, as indicated above, delay in sowing of formalin-dressed seed resulted in low effective germination. Thus the plant counts offer no direct check on the seed count. Nevertheless their results deserve notice. Slow increase in mean number of plants per foot, representing the germination delays found in all field-sowings, practically ceased by the end of January. For the plant counts made up to this time the results were:

On Dec. 21: $M_\alpha = 10{\cdot}7$; $M_\beta = 10{\cdot}8$
,, Jan. 19: $M_\alpha = 11{\cdot}4$; $M_\beta = 12{\cdot}0$
,, Jan. 28: $M_\alpha = 12{\cdot}6$; $M_\beta =$ not made.

In all these counts a per-foot fluctuation was displayed closely similar in form to that shown above to characterise seed distribution. Thus for the count of plants per foot on Dec. 21 the quintiles were:

Q. 1 = 0 – 5·7; Q. 2 = 5·7– 8·8; Q. 3 = 8·8–11·5;
Q. 4 = 11·5–15·0; Q. 5 = 15·0–23·0.

The value of $r_{\alpha . \beta}$ was small and statistically non-significant. Thus despite low effective germination the irregularity of plant population resembled that of seed distribution.

Field G.

Soil, a boulder clay and not well drained; in fair heart and well cultivated; sowing on Nov. 1 on a seed-bed which for the land and the season was good; tilth not rough but somewhat sticky after recent frosts; a 9-coulter cup drill in fair working order; Cambridge Browick wheat sown at an intended rate of 2½ bushels per acre; an excellent sample of seed.

The seed count was here confined to the work of a single coulter of the drill in order to get data for a succession of foot-lengths. Seven successions, dispersed over the acre, and amounting in all to 190 one-foot samples, made up the whole count. The values were:

M = average number of seeds per foot = 16·5
σ = standard deviation = 5·6
Frequency distribution = Table II G.

The quintiles of the frequency distribution of number of seeds per foot were, approximately:

Q. 1 = 2·0–11·3; Q. 2 = 11·3–14·1; Q. 3 = 14·1–17·9;
Q. 4 = 17·9–21·0; Q. 5 = 21·0–31·0.

These values, as a body, closely resemble the corresponding values for field D; that the upper limit of Q. 5 differs for the two fields is of no significance as an examination of Table II, lines D and G, shows. For both the fields, also, M and σ are of the same order.

The character of foot to foot fluctuation may be illustrated by one of the successions of one-foot samples from a continuous row sown by one and the same coulter. Table III contains the data with an explanatory legend.

Table III. *Numbers of seeds deposited on* 36 *successive one-foot lengths of a row sown by a single coulter. Field* G.

The succession runs from left to right in the top row of the table, then continues in the same order in the second row and so throughout.

14	18	9	2	4	11	10	7	10
14	19	13	10	18	14	7	10	17
24	22	10	14	12	22	15	15	20
15	20	13	10	17	6	18	4	18

Periodic plant counts were subsequently made. They gave a mean number of plants per foot which slowly rose, as delayed germinations

became effective, up to 14·5 on Jan. 21. Thus the effective germination was 87·8 per cent. (judged by survival up to 12 weeks from sowing). With so good an effective germination the per-foot fluctuation of the plant counts may reasonably be taken as supporting evidence of findings based on the seed count. As a fact the three plant counts made up to and including Jan. 21 showed marked concordance in all respects. Their form may be illustrated by the Jan. 21 count. This comprised 100 duplicate samples and gave a standard deviation of plants per foot = 6·1. The quintiles of the distribution of number of plants per foot were:

Q. 1 = 1 –10·6; Q. 2 = 10·6–13·1; Q. 3 = 13·1–16·8;
Q. 4 = 16·8–19·0; Q. 5 = 19·0–36.

There is thus a close general resemblance to the quintile values of the seed count for which the samples were drawn at an entirely different set of sampling-points on the field. Finally $r_{\alpha\ \beta}$ (correlation of numbers in adjoining one-foot lengths) was again very small and not statistically significant.

For field G, therefore, the fluctuations exposed by the seed count was very fully confirmed by three successive plant counts.

Field L.

Soil, a medium-heavy clay, well drained; in fair heart; until 1926 badly farmed and since then intensively worked to restore cleanness and condition; sowing on Oct. 27 on a seed-bed which, though sticky on top was firm below and in general extremely good for the land and season; an 11 coulter cup drill, new, and in perfect order; Yeoman wheat sown at an intended rate of 2½ bushels per acre; an excellent sample of seed.

At the seed count 286 one-foot samples were drawn about equally from the work of the separate coulters. The general results were:

M = average number of seeds per foot = 18·0
σ = standard deviation = 7·2
Frequency distribution = Table II L.

The quintiles of the frequency distribution were:

Q. 1 = 5·0–12·2; Q. 2 = 12·2–15·0; Q. 3 = 15·0–18·0;
Q. 4 = 18·0–22·3; Q. 5 = 22·3–39·0.

In this third field, therefore, a wide range of per-foot fluctuation is apparent, its form being closely similar to that found for the other two fields. Indeed the resemblance to field D is remarkably close both in M and Q. 1–Q. 5.

In the plant counts, increase in population ceased after the count made on Feb. 4. For this the quintile limits were close to those given above for the seed count. The plant count thus affords confirmation of the seed count. It must be pointed out that in the case of this field the mean number of plants per foot did not differ significantly from the mean number of counted seeds. With excellent seed, a good seed-bed, and skilful husbandry, effective germination was doubtless very high. But these facts suggest that a certain percentage of seeds escaped notice at the seed count. This, indeed, must be the case in every seed count. It is only when effective germination is extremely high, that the fact is demonstrable in terms of the seed and plant counts. Great care in seed counts and checks by 1000-corn weight make it certain, however, that the proportion of uncounted seeds is not such as to invalidate the inferences as to fluctuation which have been drawn. The concordance of the separate fields is a further vindication.

Field P.

This was selected as an inherently difficult field and in anticipation of a somewhat low level of husbandry. Soil, a heavy clay, badly drained and frequently water-logged in winter; in poor heart and cultivated at minimum expenditure; sowing on Oct. 21 after rough preparation but in a period of favourable weather; a 10-coulter cup drill much worn in all the working parts; Yeoman wheat sown at an intended rate of $2\frac{1}{2}$ bushels per acre; a bad seed sample as later explained.

Four successions of one-foot lengths were employed at the seed count, in all 149 samples. The values were:

M = average number of seeds per foot = 11·9
σ = standard deviation = 5·9
Frequency distribution = Table II P.

The frequency distribution, based on only 149 samples, is less smooth than those of the other fields. Its approximate quintiles are:

Q. 1 = 0 – 6·6; Q. 2 = 6·6– 9·7; Q. 3 = 9·7–12·8;
Q. 4 = 12·8–16·6; Q. 5 = 16·6–25·0.

Thus, in the face of an intention to sow at about the rate used on the other fields, the seeding was here very thin. It displays, however, much the same measure and exactly the same form of per-foot irregularity as the other three fields.

As with field G any one of the successions of foot-lengths forcibly

illustrates the fluctuations of seed deposition. Table IV, with its explanatory legend, is given as an example.

Table IV. *Numbers of seeds deposited on* 31 *successive one-foot lengths of a row sown by a single coulter. Field* P.

The succession runs from left to right in the top row of the table, then continues in the same order in the second row and so throughout.

8	13	17	7	23	9	12	7	14
8	15	7	5	11	16	10	12	9
8	7	20	10	15	14	20	15	8
6	23	19	10					

The seed sample was well dressed but included 18 per cent. of "sprouted" corns as shown by a full test of germination. If, then, the mean number of seeds sown per foot were 11·9, as stated above, the mean number of plants per foot should be 9·8. Actually, when the maximum was reached—at a count made on Feb. 1—the mean was 10·4, the standard deviation of the per-foot distribution being 5·53. It is probable that a small proportion of seeds, other than those actually "sprouted," failed to produce seedling plants. Consequently the effective equality of mean number of counted seeds and mean number of counted plants here, as for field L, suggests that a small proportion of seeds escaped notice in the count. This inevitable difficulty does not, however, invalidate the general evidence of the plant count. For this count the quintiles were:

$$\text{Q. }1 = 0 - 6{\cdot}2;\ \text{Q. }2 = 6{\cdot}2 - 8{\cdot}9;\ \text{Q. }3 = 8{\cdot}9 - 11{\cdot}8;$$
$$\text{Q. }4 = 11{\cdot}8 - 15{\cdot}0;\ \text{Q. }5 = 15{\cdot}0 - 26{\cdot}0.$$

These values, of general similarity to the quintiles of the seed count, support by plant-population evidence the suggestion that the seed was deposited at a highly fluctuating per-foot rate.

In census counts prior to the series here described, no seed data were obtained. But the numerous plant counts lead to conclusions upon plant-density irregularity of exactly the same kind as have been reached in the preceding passages. Facts are recorded in earlier papers for a field of Yeoman wheat in 1923–4 (1), a field of Little Joss wheat in 1924–5 (1), and fields of Plumage Archer barley in 1924–5 and 1925–6 (2). Tentative observations (5) on sugar-beet and mangolds afford further confirmation of the general principle.

Of the four fields described in detail, three were seeded by drills in good order; the drill used on P was in bad order and in particular the teeth of the gear wheels were much worn. For all four fields the intended seed rate was 2½ bushels. The same wheat, Yeoman, was sown on D, L

and P, but whereas on D and L about 18 seeds per foot were found, on P the number was only 12. Allowing for failure to find a certain proportion of the seeds, it must yet be inferred that field P was definitely under-seeded. Wear in the drill was probably the prime cause of this. Relative regularity of seeding on the fields may be expressed by the coefficient of variation ($V = 100\sigma/M$) for the per-foot distributions. The values of V were:

$$D = 40{\cdot}1 \qquad G = 34{\cdot}0 \qquad L = 40{\cdot}7 \qquad P = 49{\cdot}6.$$

Since, in all subsequent plant counts the value of V was highest in the case of field P a connection may be presumed between irregularity of seeding and drill-wear.

The degree of irregularity of seeding on these four representative fields may be more fully expressed by the mean number of seeds per foot of the quintiles of the distributions. These appear in Table V.

Table V. *The mean value of seeds per foot for the quintiles of the fields* D, G, L *and* P.

Field	Q. 1	Q. 2	Q. 3	Q. 4	Q. 5	Mean for the acre
D	9·8	14·6	17·3	20·4	26·5	17·7
G	8·8	13·5	16·2	19·9	24·2	16·5
L	10·2	14·1	16·9	22·4	26·4	18·0
P	3·5	8·8	11·9	15·1	20·4	11·9

Even on a carefully sown field like L an aggregate of one-fifth of the acre was seeded at a mean per-foot rate of 10·2, the remaining one-fifth aggregates being seeded at 14·1, 16·9, 22·4, and 26·4. On field P only one-fifth of the acre reçeived a seeding as dense as the averages for the entire acres of D and L. In further illustration of seeding fluctuation the quintile means may be converted into bushel rates. Field L, the most carefully sown of all, did actually receive about the intended amount of 2½ bushels per acre. The mean number of seed counted per foot was 18·0. This may therefore be taken to correspond to 2½ bushels per acre and the mean seed rates of the quintiles may be calculated from the values for field L in Table V. These quintile seed rates are, in bushels per acre:

$$Q.\ 1 = 1{\cdot}42;\ Q.\ 2 = 2{\cdot}00;\ Q.\ 3 = 2{\cdot}35;\ Q.\ 4 = 3{\cdot}11;\ Q.\ 5 = 3{\cdot}70.$$

Five adjoining acres on a field, sown the same day, but respectively at these rates, would not be expected to give by any means the same yield. But the foregoing facts suggest that in aggregate a piece of 5 acres would be found to be constituted by five equal portions with

the above respective seed rates. Similar inferences are to be drawn from the experimental evidence derived from the other three fields.

Irregularities of plant density, of an order specified by the results here discussed, may be said to rest upon abundant proof. The many hazards of plant life even on good soil and under careful husbandry have made it necessary to assess the responsibility of effective drill action by counts of seed deposited. Many difficulties attend such counts, which are, however, the only available form of evidence. For this reason the facts of the four experimental fields have been discussed at length. They appear to leave no escape from the conclusion that in the operation of drilling is to be found the main cause of plant-density fluctuation in typical fields of corn.

§ IV. THE PER-INCH DISTRIBUTION.

It is clear that distribution per foot cannot be more than a partial disclosure of irregularities in seed or plant dispersion. On a foot with 12 seeds there may be 10 in the first 2 in. and 2 somewhere in the remaining 10 in. Or there may be regularly one per inch. That scatter within the foot is highly irregular is a convincing conclusion from making counts. For a full appreciation of irregularities more intimate recording is therefore necessary. From such records may conceivably come some clue to the idiosyncrasies of drill action in the field. Finally, exact disposition of seeds and plants is biologically important in relation to inter-plant competition. On the two hypothetical foot-lengths with 12 plants discussed above, influences of competition would be entirely different. And localised crowding and gaps would probably, from what is known of the spatial influence in wheat (*vide* (6)) carry an entirely different significance at densities of, say, 8 and 16 plants per foot.

Upon these considerations it was decided to make counts of per-inch distribution. This was impracticable with seeds and counts were therefore made on plants at a time when the population was at full strength but before tillering had commenced. The work was carried out on fields D (Jan. 28), L (Feb. 1), and P (Feb. 4). After this, extreme wetness of soil prevented work on field G. The method employed was arduous (in cold weather) but successful. Pegs an inch wide and protruding about an inch and a half from the soil, were inserted at each end of every foot-length sample (100 suitably dispersed samples on an acre). A sheet of glass about $15'' \times 4''$ was rested on these pegs and an ink-mark made exactly over every plant. Then a sheet of squared paper

(ruled in inches and twelfths), 12 in. long, was placed face down on the glass exactly over the foot-length, and blotted. Rough surface paper was used so that a small "blot" of ink recorded on the squared paper

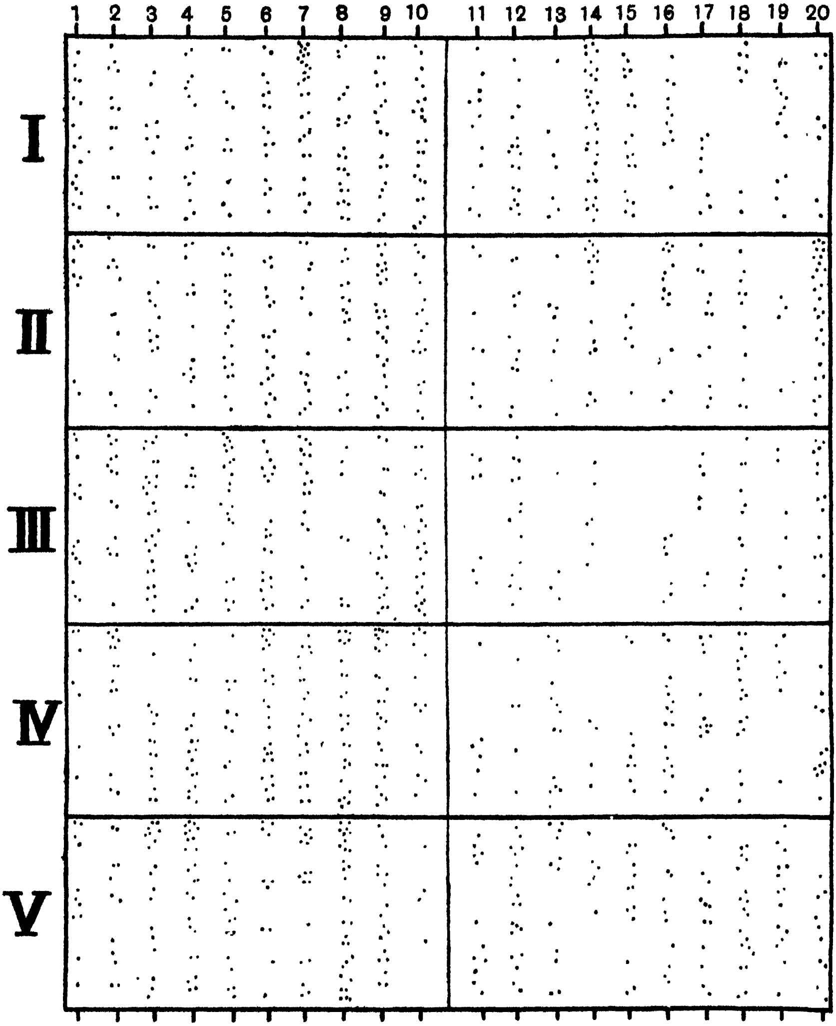


Diagram I. Fifty foot-lengths from field L and from field P arranged at random in 10 rows (1–10 for L and 11–20 for P) each consisting of five (I–V) one-foot lengths. Each dot represents the exact position of a single plant (drawn to scale).

the exact position of every plant in the sample. One hundred sheets, prepared in this manner, thus afforded a representation of the population-dispersion on the acre.

Presentation and analysis of the considerable body of data so obtained involves certain difficulties. In the passages which follow the

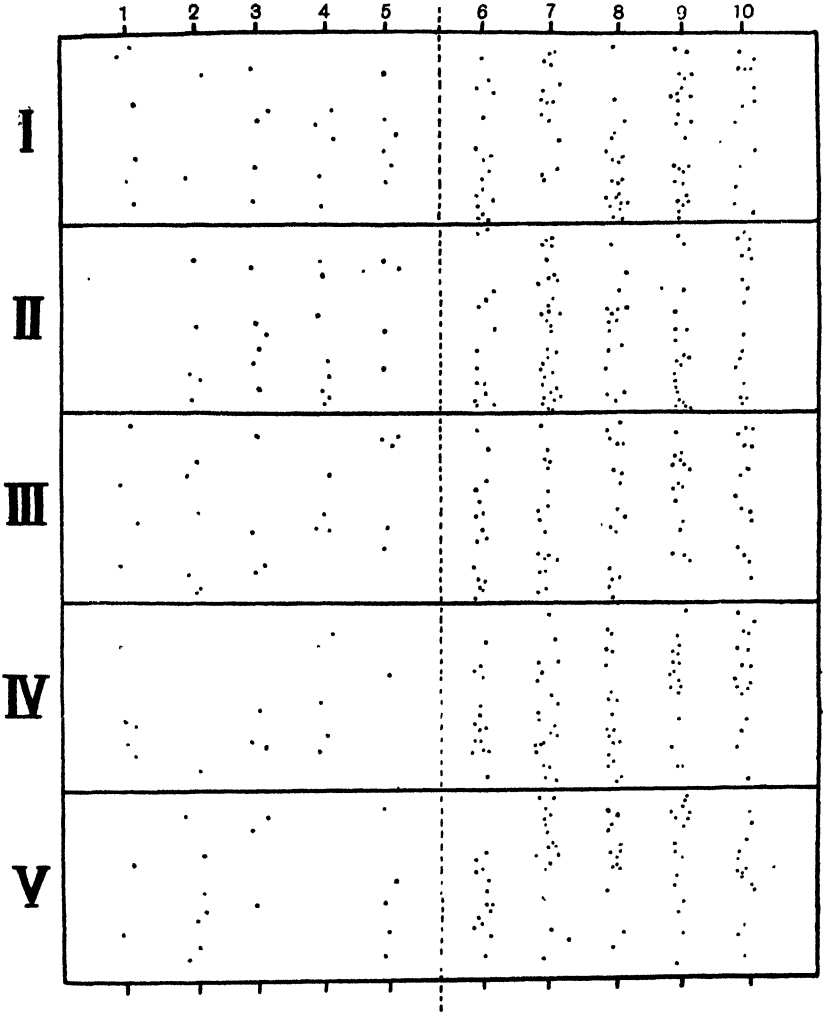


Diagram II. For field P showing plant populations (exact position of every plant) in the first and fourth quartiles of the per-foot frequency distribution. As in Diagram I the actual sample feet are presented in drill rows 5 feet long.

aspects of per-inch population density are discussed in turn. Analytical treatment is reserved for §§ V and VI (*infra*).

An ocular appreciation of precise plant density is afforded by

Diagram I which represents fields L and P side by side. For each field are shown fifty one-foot lengths drawn at random from the count of 100

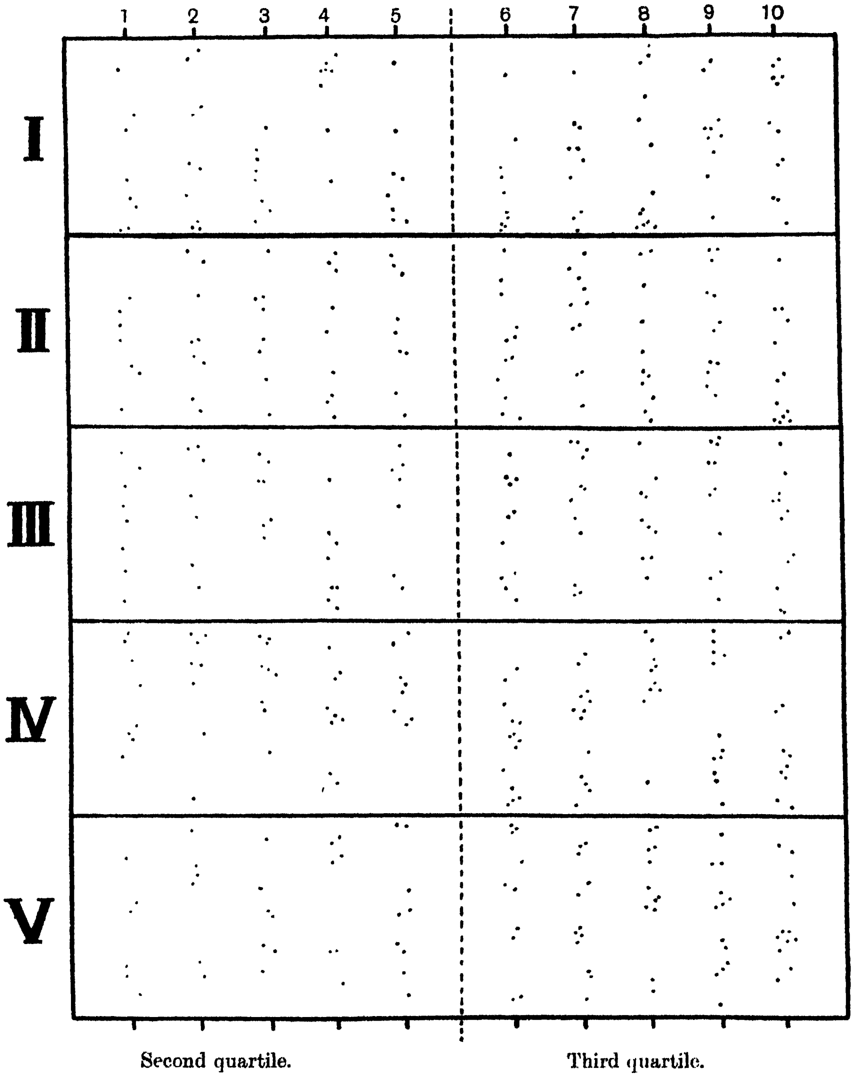


Diagram III. For field P showing plant populations (exact position of every plant) in the second and third quartiles of the per-foot frequency distribution. As in Diagram I the actual sample feet are presented in drill rows five feet long.

sample feet. These lengths are arranged in 10 rows (1–10 for L and 11–20 for P) which, since density fluctuations are dispersed at random over the field (*vide* § VI *infra*) may be regarded as 10 typical rows of

plants in the field. Every row is 5 ft. long, the feet being marked I–V on the diagram. A plant is represented by a dot and the dots are inserted accurately to scale from the actual counting sheets. From the discussion of § III (*supra*) it appears reasonable to treat this plant dispersion as a fair reflection of scatter of seed by the drill.

The marked difference in general density between fields L and P is apparent from the diagram. On both, the intended seed rate was $2\frac{1}{2}$ bushels per acre. It is to be inferred that field P was much under-

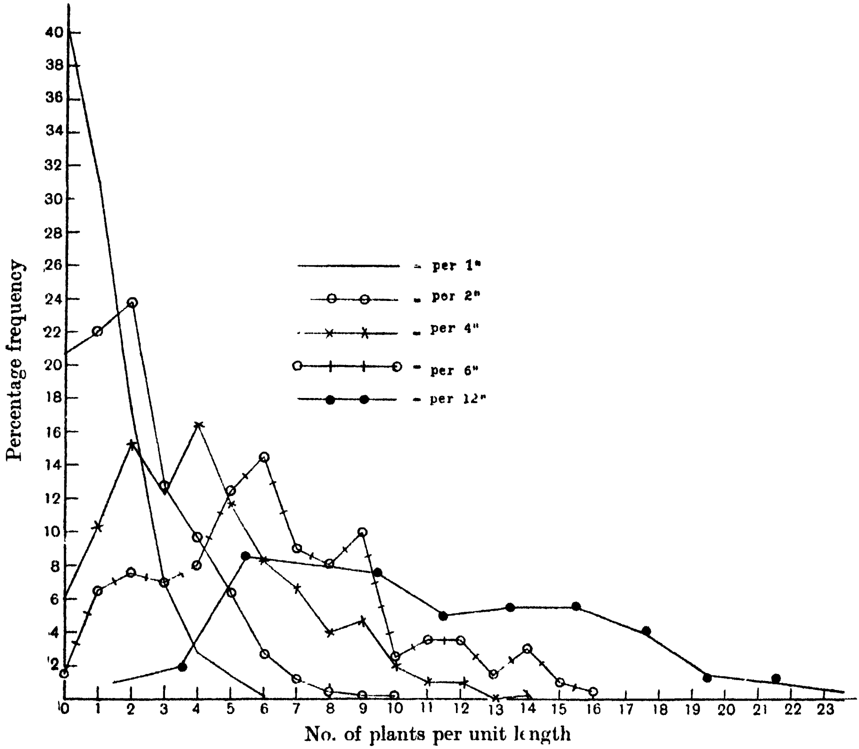


Diagram IV. Field D. Frequency distribution (in percentages) of number of plants per 1, 2, 4, 6 and 12 inches. The curve for 12 inch has been smoothed by using a class interval of 2 plants per 12 inch.

seeded, a circumstance probably attributable in no small measure to the worn condition of the drill. The marked per-foot fluctuation is strikingly shown on the diagram, especially for field P. Variable arrangement within the foot is also apparent. An example is the regular distribution of foot 11 . I (*i.e.* row 11, foot I) in contrast with the unevenness of foot 18 . I.

In § III (*supra*) fluctuations in density were illustrated for all the fields by the range-limits and mean values of the quintiles of the per-foot

distribution. Diagrams II and III are a further illustration drawn from field P. For simplicity they are based upon the distribution quartiles. It may be said that on the acre of field P, in aggregate,

$\frac{1}{4}$ acre was seeded as in	Diagram	II	left-half	(Q. 1)
$\frac{1}{4}$,,	,,	III	left-half	(Q. 2)
$\frac{1}{4}$,,	,,	III	right-half	(Q. 3)
$\frac{1}{4}$,,	,,	II	right-half	(Q. 4)

If Diagram II presented the seed distributions on two separate fields seeded at the same intended rate it would disclose a surprising difference. As a difference between two equal aggregates, each a quarter of one and the same acre it is even more striking.

The population of the individual inches must be noticed next. It is summarised in Diagrams IV, V and VI for fields D, L and P respectively (curves of percentages of inches with 0, 1, 2, ... plants each). On field L, well managed and with a high effective germination, 25 per cent. of the inches carry no plants; field D with low effective germination resulting from delay after dressing the seed with formalin, has 40 per cent. of blank inches; field P, badly managed, has exactly half its inch-lengths without plants. Localised overcrowding is clearly shown. Thus in field L some 22 per cent. of the inches carry three or more plants each. The remaining curves of Diagrams IV, V and VI show (as the legends of the diagrams explain) the corresponding distributions for lengths of 2, 4, 6 and 12 inches respectively. These distributions were obtained direct from the original counting sheets and are required for the analytical purpose of § V (*infra*). The steady change in general form from the extreme asymmetry of the one-inch distribution progressively through the 2, 4, and 6 inch curves to the approximate normality of the 12 inch distribution is to be expected. Its exact features are examined later.

§ V. Analytical Observations on the Per-inch Distribution.

With the detail of distribution, inch by inch, it is now possible to test whether seed deposition is purely random or governed by some bias or idiosyncrasy of drill or soil. Three tests are applicable:

(i) To ascertain whether the frequencies of inches with 0, 1, 2, ... plants each are a binomial series.

(ii) To examine the frequency of successions of 2, 3, ... inches in which all the inches have 0 plants; and similarly for 1, 2, ... plants per inch on successions of adjoining inches.

(iii) To compare the distribution per inch over separate quintiles of

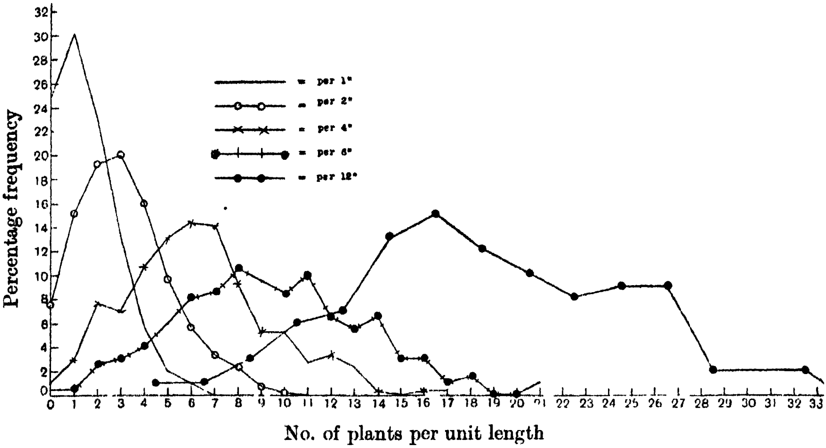


Diagram V. Field L. Frequency distribution (in percentages) of number of plants per 1, 2, 4, 6 and 12 inches. The curve for 12 inch has been smoothed by using a class interval of 2 plants per 12 inch.

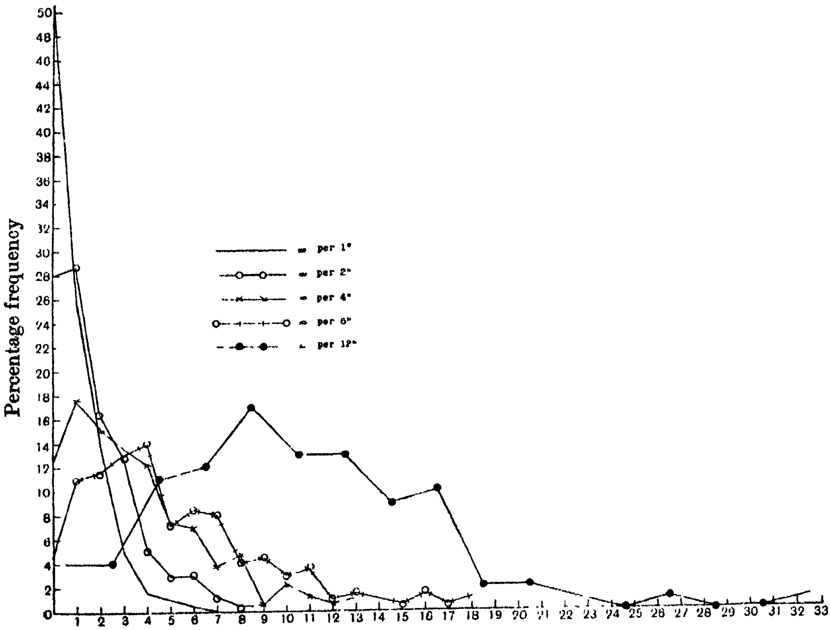


Diagram VI. Field P. Frequency distribution (in percentages) of number of plants per 1, 2, 4, 6 and 12 inches. The curve for 12 inch has been smoothed by using a class interval of 2 plants per 12 inch.

the whole distribution for an acre, and to explore certain questions of adjacency correlation.

Illustrative data for Test (i) may be taken from Diagram IV field D (per-inch distribution):

No. of plants per inch	0	1	2	3	4	5	6
Per cent. of total inches	40·5	31·0	17·3	6·9	2·8	1·4	0·1

If distribution is governed solely by chance then these percentage frequencies should form a binomial series. The theory of the test may be thus briefly expressed. Let there be z causes controlling the number of seeds deposited upon an inch of drill row. Number of seeds picked up by the individual cup of the drill, velocity of drill from moment to moment, varying size of seed, etc. may be conceived as among the governing causes. Suppose that for every one of these causes the chances of "success" and "failure" are respectively p and q where $p+q=1$. "Success" implies the chance operation of any one of the causes in such manner as to favour seed deposition; "failure" in such manner as to militate against it. Then the frequency distribution of number of seeds per inch will be given by the terms of $(q+p)^z$. The quantities p, q and z are, of course, unknown. From the frequency-distribution given above for field D (as also from those for L and P) it must be concluded that p is very small for the distribution is markedly asymmetrical. Now the limiting form attained by the binomial distribution when either p or q is very small (but $p \,.\, z$ or $q \,.\, z$ is still finite) is a Poisson Series. In this limiting form the square of the standard deviation is equal to the mean ($\sigma^2 = M$) [for algebraic proofs see G. Udny Yule, *An Introduction to the Theory of Statistics*, Griffin and Co., Ltd., London, 1927. Eighth edition, revised, pp. 366–9]. Calculation shows that for field D, $\sigma^2 = 1{\cdot}36$ and $M = 1{\cdot}05$ and the distribution therefore appears to be not binomial. For the three fields from which data are available the values are:

Field	σ^2	M
D	1·36	1·05
L	1·89	1·55
P	1·32	0·86

In all three fields therefore $\sigma^2 > M$. It is inferred that seed distribution is not purely random but that one or more forms of bias are operative.

Several assumptious have necessarily appeared in the above reasoning. Thus it is taken for granted that p and q have constant values for all the individual inches of drill row concerned. Alteration in their value would naturally affect the form of the distribution[1]. Again, it is possible

[1] A question of distribution with singular resemblance to this is treated by Yule and Greenwood (7) who furnish a full theoretical consideration of the general case.

that on one small area seed distribution is random and on another biassed. As a test of possibilities of this kind the values of σ^2 and M have been determined for the separate quintiles of the per-foot distribution for all three fields. These quintiles correspond, of course, to aggregated areas over which the drill was depositing seeds at different rates. To simplify calculations, approximate quintiles were employed. These represent the nearest approach to partition of the frequency distribution into five equal parts which is possible without dividing up the frequencies of the classes of the distribution. Table VI shows the results.

Table VI. *Values of σ^2 and M for the separate (approximate) quintiles of the frequency distribution of number of plants per inch.*

	Field D		Field L		Field P	
Quintile	σ^2	M	σ^2	M	σ^2	M
Q. 1	0·69	0·48	1·15	0·87	0 29	0·27
Q. 2	0·79	0·76	1·47	1·25	0·72	0·59
Q. 3	1·13	1·00	1·60	1·53	1·05	0·82
Q. 4	1 24	1 28	1·59	1·85	1·16	1·03
Q. 5	1·85	1·63	2 24	2·29	1 98	1 52

It is seen that with three exceptions (Q. 4 for D; Q. 4 and Q. 5 for L) σ^2 always exceeds M as was the case with values derived from the complete distribution for every field. But there appears a tendency for the excess of σ^2 over M to be greater in the low quintiles than in the high.

The general conclusion from this test is therefore that seed distribution by the drill is not entirely random. Some bias or non-random characteristic must operate and its action appears to be most marked upon those elements (foot lengths of row) of the field where seeding is thinnest. This bias is evidently not a marked one.

The second test of random or non-random distribution is an extension of the first. Of the inches with 0 plants some will be solitary, *i.e.* adjoining at each end an inch with one or more plants. Others will belong to a succession, *i.e.* two or more consecutive inches each with 0 plants. A succession of, say, two 0-plant inches may be a solitary succession, *i.e.* bounded at each end by an inch with one or more plants. Or it may be part of a larger solitary succession. Thus a solitary succession of 5 in. each of 0 plants also constitutes five single 0-plant inches, four non-solitary 2-inch successions, three non-solitary 3-inch successions, and two non-solitary 4-inch successions. Let the probability of a 0-plant inch (as opposed to an inch with one or more plants) be α. Its value is the

proportion of 0-plant inches to total inches. If the distribution is random then the expected frequencies of successions in a total of n inches are proportional to:

$$\begin{array}{lll} \text{1-inch} & & = \alpha\,.n \\ \text{2-inch successions} & & = \alpha^2.n \\ r\text{-inch} & ,, & = \alpha^r.n. \end{array}$$

It can be shown that the expected frequencies of the corresponding solitary successions are obtained by multiplying the above frequencies by $(1 - \alpha)^2$. The test may be illustrated from field D for which $\alpha = 0{\cdot}4042$. Observed and expected values are:

	Length of 0-plant succession								
	1	2	3	4	5	6	7	8	9
Actual frequency (%)	60·61	19·70	7·95	4·55	4·17	1·14	1·52	—	0·38
Calculated frequency (%)	59·58	24·08	9·72	3·94	1·59	0·66	0·28	0·10	0·03

The agreement in general form between expected and observed distributions is clear, but in a few frequencies there is considerable divergence.

Without attempting a precise test of fit it may be noted that the two distributions are very closely similar but that the observed frequencies are greater than the expected for all successions of four or more inches with no seeds. There is therefore some bias but it appears reasonable to infer that the distribution is very largely random. Corresponding tests may, of course, be carried out for one plant per-inch successions, and so on. There appears nothing in the data from fields D, G and L (on which per-inch distribution was observed) which militates against the conclusion that per-inch distribution is, if not perfectly random, marked only by some very slight bias.

The third test of random distribution has now to be considered. If seed distribution is purely random, then the number on any unit length of drill row is independent of (or not correlated with) the numbers on the adjoining unit lengths. From the circumstances of seed distribution it is conceivable that degree of correlation may vary with the unit of length employed. Now data are available for units from one inch to one foot. They are derived from the plant count described in § IV (*supra*), but for reasons already given it is considered legitimate to make deductions upon seed distribution from the facts of plant distribution. To ascertain the correlation between numbers of plants on adjoining lengths of drill row, for 1 inch, 2 inch, ... 12 inch lengths in turn, is thus the essence of this test. It is convenient, before investigating these correlations, to deal with a related consideration.

Fluctuations in seeds and plants per foot, have been fully described

in § III (*supra*). It was shown, for example, that on field L, the quintiles or equal one-fifth aggregates of the per-foot distribution of seeds, had the following limits:

Q. 1 = 5·0–12·2; Q. 2 = 12·2–15·0; Q. 3 = 15·0–18·0;
Q. 4 = 18·0–22·3; Q. 5 = 22·3–39·0.

Now theoretically, the low seed rate of the aggregate Q. 1 might be explicable in more than one way. It might arise from a very high proportion of blank (0 seeds) inches with dense seeding of the few remaining inches. Or it might represent a very low but fairly uniform seeding on all the individual inches. Corresponding alternative explanations might be offered for the medium seeding of Q. 3 and the dense seeding of Q. 5. These possible explanations may be tested by examining the per-inch constitution of the separate quintiles of the per-foot distribution [using the plant count data of § IV (*supra*)]. For this purpose it is simplest to employ approximate quintiles as in the first test described in this paragraph (approximate quintiles represent the nearest approach to partition of the frequency distribution into five equal parts which is possible without dividing up the frequencies of the classes of the distribution).

Table VII. *Field* L. *Percentage number of inches with* 0, 1, 2, ... *plants each in the separate (approximate) quintiles of the per-foot frequency distribution for the whole field.*

	Number of plants per inch						
Quintile	0	1	2	3	4	5	6–7
Q. 1	47·7	29·6	13·9	6·0	1·9	0·9	—
Q. 2	31·9	34·1	18·8	10·1	3·3	1·4	0·4
Q. 3	22 7	29·9	28·0	13·6	3·4	0·8	1·5
Q. 4	12·2	32·9	26·4	17·6	8·6	1·4	0·9
Q. 5	10·1	23·7	26·3	18·9	12·3	6·1	2·6

Table VII discloses the per-inch constitution of the quintiles of the distribution of number of plants per foot on field L. The essential difference among the quintiles is observed to be a sharp decrease in the percentage of blank inches in the order Q. 1–Q. 5. With this is a more or less regular increase, in the same order, of percentages of inches with 1, 2, ... plants each. Broadly, then, on the thinly seeded elements of the field, numerous blank inches and thin seeding of the remaining inches are associated. The converse association marks the more thickly seeded parts (cf. Q. 5). Some degree of correlation between the populations of adjoining inches is therefore suggested.

Further illustration is afforded by Table VIII. In this table "sown inch" implies an inch carrying one or more plants; "sown length" denotes the total inches belonging to some specified length on every one of which are one or more plants. Column (*c*) clearly shows that a relatively low proportion of sown inches is characteristic of the lower quintiles, *i.e.* the thinly seeded aggregates of the field. Columns (*d*)–(*j*) present, in terms of sown length, what Table VII shows in terms of total length of row (including blank and sown inches). The proportion of sown inches having only one plant each decreases in the order Q. 1–Q. 5. In the case of two plants per inch the quintiles show no regular difference. For the more thickly populated inches there is a steady rise in the order Q. 1–Q. 5. The association already suggested is thus again to be inferred. Numerous blank inches with thin seeding of the remainder mark the lower quintiles, and conversely. Fields D and G show precisely similar results and the data are therefore not given. On field P, with a very low all over average of plant density, the percentage of blank inches is in Q. 1 = 77·7 and in Q. 5 = 28·8—a sharp contrast with field L although the intended seed rate was the same on both fields. These considerations with others discussed in § VI (*infra*) point to the necessity of studying correlations between adjoining lengths of row.

Table VIII. *Field* L. *For the separate* (*approximate*) *quintiles of the per-foot distribution, showing for the "sown length"* (*i.e. the total inches on all of which are one or more plants*) *the percentage number of inches having respectively* 1, 2, ... *plants per inch.*

	Average plants per inch		Ratio (%)	Number of plants per inch					
	Including all inches	For sown inches only	sown/total inches	1	2	3	4	5	6–7
Quintile	(*a*)	(*b*)	(*c*)	(*d*)	(*e*)	(*f*)	(*g*)	(*h*)	(*j*)
Q. 1	0·87	1·67	52·3	56·6	26·6	11·5	3·5	1·8	—
Q. 2	1·25	1·83	68·1	50·0	27·7	14·9	4·8	2·1	0·5
Q. 3	1·54	1·99	77·3	38·7	36·3	17·6	4·4	1·0	2·0
Q. 4	1·87	2·12	87·8	37·4	30·0	20·0	10·0	1·6	1·0
Q. 5	2·30	2·54	89·9	26·3	29·3	21·0	13·7	6·8	2·9

For correlations between adjoining one-foot lengths there is a considerable body of evidence. On fields D and G the seed count samples were so dispersed as to give successions of one-foot lengths. The foot-foot correlations determined from these successions were low and statistically non-significant. Data from plant counts afford confirmation. It was explained in the opening passages of § III (*supra*) that on some fields duplicate plant count samples were drawn. That is, at every sampling point, two adjoining one-foot lengths were observed. Data were

obtained from these duplicates at each of the periodic counts of plant population. Of the fields described in this paper, D and G were sampled by duplicates; all the fields described in earlier papers (*vide* (1) and (2)) were so sampled. The whole body of results accords with the findings from the seed counts on fields D and G. Some correlations are positive, some negative; all are low; not one is statistically significant (in terms of its own standard error). It thus appears certain that the number of seeds deposited by the drill on any one-foot length of row is practically independent of the number on the preceding or next following foot. Distribution of seeds per foot is purely random.

Correlations between numbers of plants on adjoining one-inch lengths, two-inch lengths, etc. are derivable from the count of plants per-inch. Several have been calculated, but, as with one-foot lengths, all were very low and statistically non-significant. Certain statistical obscurities seem inherent. Thus, for all the inch-inch correlations evaluated, the coefficient was positive though non-significant. For field D the correlation (inch-inch) was determined for the separate (approximate) quintiles of the per-foot distribution. Again, the values were positive but not significant. The frequency distribution of plants per inch was, for all fields, markedly asymmetrical. In consequence the entries in the inch-inch correlation tables were mainly concentrated in the upper positive quadrant. The general form of the table suggested the possibility that a correlation subsisted in this quadrant but not in the other quadrants, especially the negative ones. It has appeared impossible, however, to press the correlation analysis beyond this point. The fact that the inch-inch correlations, though too low to signify in terms of their own standard errors, were all positive, suggests a small and possibly inconstant bias or departure from purely random arrangement such as was indicated by the two other tests already applied.

Further evidence of the existence of a correlation between small adjoining unit lengths appears from an examination of standard deviations. If variables X_1 and X_2, having standard deviations σ_1 and σ_2, be correlated to a degree r, then the standard deviation σ of their sum $(X_1 + X_2)$ is:

$$\sigma^2 = \sigma_1^2 + \sigma_2^2 + 2r\sigma_1 . \sigma_2 .$$

Now the distribution of number of plants per two-inch length is formed by sums of frequencies on pairs of adjoining inches. Distribution per six-inch length is similarly the distribution of sums of frequencies of successions of the two-inch lengths. Clearly therefore the correlation between adjacent lengths, for 2 inch-, 3 inch-, ... lengths, is deter-

minable. The appropriate standard deviations can, of course, be calculated by use of the per-inch data. The method was applied, for fields D, L and P (there was no inch count of plants on Field G). Coefficients of correlation were deduced for one-inch, two-inch, and six-inch lengths. All were low and statistically non-significant. For both one-inch and two-inch lengths all were positive; for the six-inch lengths field D gave a negative and fields L and P a positive value. Thus this further examination appears to suggest that purely random deposition of seed by the drill is slightly modified by a tendency towards correlation between deposits on adjoining very short lengths of row.

After much tedious analysis it must be concluded that seed distribution by the drill, from point to point along any one coulter row, is, in practical terms, random. This conclusion is of fundamental importance in seeking, as in § VI (*infra*), to apportion responsibility for irregularity of plant population, between the drill and the tilth. It further suggests that imperfections in the drill are traceable, not to some simple bias, but to general mechanical action. As here used, mechanical action implies the inherent functioning of the drill with the superimposed disturbances induced by tilth irregularity.

§ VI. Influences of Drill and Tilth.

Variability from place to place is well known to be inherent in the soil of every field. On any marked acre there may be found a steady "drift" of fertility or physical condition from end to end. Or large, exceptional "patches" may occur. There are also smaller irregularities and patches of diverse kinds and sizes. Evidence of these variations or irregularities is furnished by every tillage operation and at all stages in the growth of a crop. The best of seed beds is marked by local unevenness which in large measure is traceable to inherent soil variation. An observer following the seed drill cannot fail to be impressed by effect upon velocity, jolting, bumping of coulters, and other interferences produced by tilth irregularity. In the foregoing paragraphs it has been shown that along every row of seed deposited by the drill there are rapid fluctuations in density (number of seeds per foot or per inch). These fluctuations must reflect in part inherent properties of drill mechanism and in part disturbances in drill action induced by tilth irregularity. Definite tests of drill mechanism, free from tilth disturbance, are described in § VII (*infra*). To investigate tilth disturbance, by direct test would involve highly complicated procedure. Indirect test is possible, however, by means of census counts.

Census samples are regularly distributed all over the experimental acre and, as has been shown, 100 samples are satisfactorily representative of an acre. If, therefore, one portion of the acre—be it one end or side or a considerable patch—is such as to induce unusually low or high fluctuation in seed distribution, the fact should be reflected by the samples from that portion. Where duplicate samples have been drawn (*vide* § III *supra*) these considerations may be made to take the form of specific tests in terms of the correlation between members of the pair.

In comparing fluctuations in density of seeds (or plants) on separate considerable portions of the experimental acre the coefficient of variation (V) has been employed ($V = 100\sigma/M$ where σ and M are respectively the standard deviation and mean of the frequency distribution of number of plants per foot). On some of the fields comparisons have been made between fluctuation at opposite ends of the acre, on areas of one-fifth acre in diagonally opposite corners, and in other similar ways. In one field, heavy and sloping, there was a regular gradation in average number of plants per foot from top to bottom; but there was no corresponding gradation in fluctuation. All tests of this kind have suggested that fluctuations in density of seed (and plants) from point to point along the row characterise the whole acre. Thus they are not attributable in any way to major soil variations, or the major tilth irregularities to which these give rise. Average amount of seed deposited per unit length of row, or average survival rate, may be affected by major variations, but that is a consideration distinct from the fluctuations under discussion.

The question may be approached in another way by examination of the location upon the experimental acre of samples having various degrees of density of plants. Patches or areas by which degree of fluctuation was specifically affected should be readily perceptible. Diagram VII is a ground plan of the experimental acre on field D. For simplicity five gradations of plant density are recognised, viz. the approximate quintiles of the frequency distribution of number of plants per foot for the whole acre. The 100 samples constituted 16 oblique "traverses" each of 6 samples with a seventeenth traverse (not shown) of 4 samples; correspondingly they form 6 "rows" each of 16 samples (with a seventeenth, not shown, in 4 of the 6 rows). The dimensions of the acre, which is not shown to scale, were 60 × 80·5 yards. As explained in the legend below the diagram, conventional signs are employed to indicate the degree of density (quintile) into which every sample falls. General inspection

suggests that the samples belonging to any one quintile are scattered at random over the acre. A simple statistical test may be applied. Into the first approximate quintile of the whole distribution there fall 23

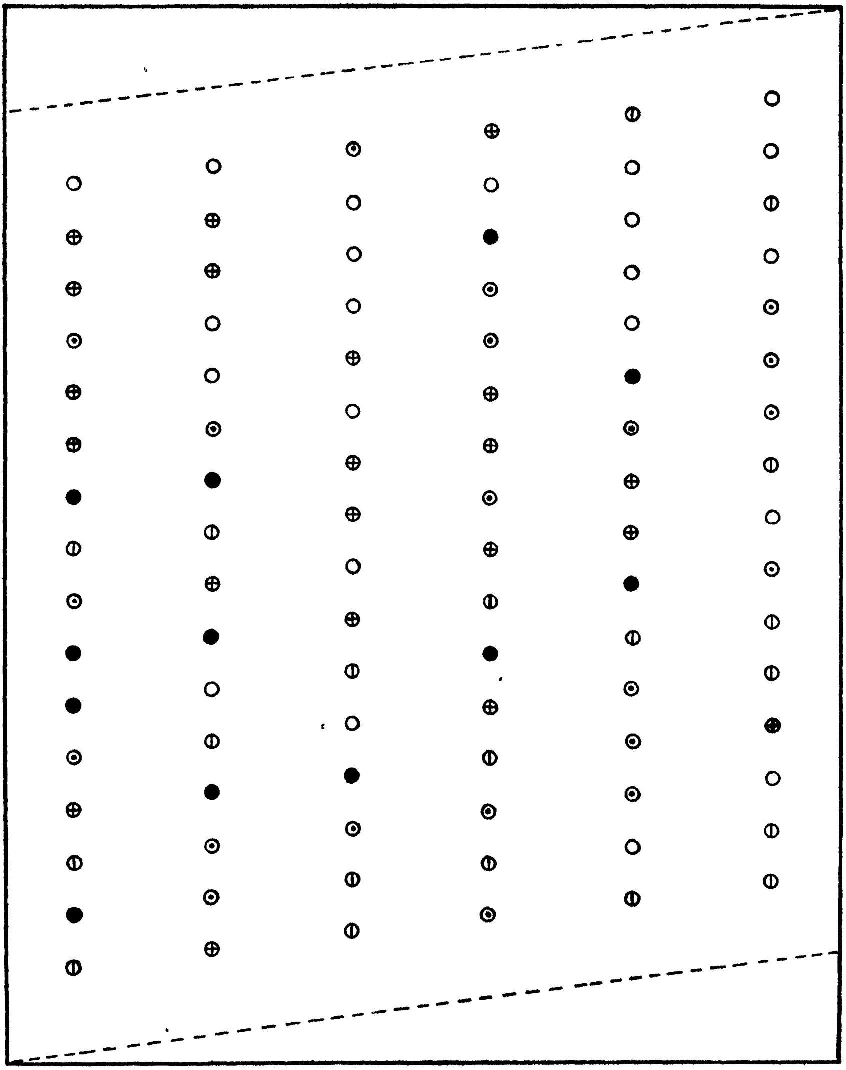


Diagram VII. Field D. Count made on April 23, 1927; the position on the acre of the samples belonging to the separate quintiles of the frequency distribution of number of plants per foot.

○ 0– 6 plants per foot
⊙ 7– 9 ,,
⦶ 10–12 ,,
⊕ 13–16 plants per foot
● 17–23 ,,

samples. On random basis therefore the expectation is 23 per cent. first quintile samples on any one row or traverse. In the case of rows (there being 16 samples per row) the expected distribution, in random basis, of number of first quintile samples per row is given by $(p+q)^{16}$, and therefore for a total of six rows is:—

0	*1*	*2*	*3*	*4*	*5*	*6*	*7* or more
0·09	0·44	0·98	1·37	1·33	0·95	0·52	0·32

The actual numbers of such samples in the six rows, left to right (Diagram VII), are 1, 4, 6, 1, 5, 5. With so few rows available it is impossible to speak of "goodness of fit" but the absence of any marked bias appears to be indicated. Application of this form of test to all the data supports the conclusion that major tilth irregularity has no share in the fluctuations of seed and plant density under discussion. [In a very small number of cases the deviation from expectation very slightly exceeds three times the probable error; in no case is three times the standard error exceeded; since the quintiles represent a very arbitrary density gradation these few slight exceptions have little significance.]

Finally a test may be based on the correlation between numbers of seeds or plants on adjacent unit lengths of row. Let there be supposed a small "patch" on the field of such nature as to induce unusually heavy deposition of seed by the drill. Then if two adjoining samples be observed in this patch, each a one-foot length of row, the number of plants in each sample should be unusually high. If effectively exceptional patches occurred frequently on the field then there should be a fairly high correlation between adjacent feet. It has been explained (§ V *supra*) that in all cases where duplicate one-foot samples were drawn, the adjacent feet correlation was not only low but lacked statistical significance. It cannot be supposed that in general one sample of the pair will fall within a patch and the other outside. Accordingly no reason exists for attributing density fluctuations to small "patches" in the tilth. Correlation between smaller adjacent unit lengths (1, 2, 4 and 6 inches, described in § V *supra*) similarly excludes the possibility that density fluctuations mainly reflect even the most localised irregularities of tilth.

That no systematic association subsists between tilth irregularity and fluctuations in seed or plant density along the row, is suggested by all the tests which have appeared applicable. Drill action is nevertheless disturbed by unevenness of tilth. The nature of this disturbance must be highly irregular and at present lies beyond the scope of analysis.

It therefore remains to study the fluctuation inherent in the drill mechanism.

§ VII. A Preliminary Analysis of Drill Mechanism.

Analytical tests are an essential in machine manufacture. They have a place not only in the stages of designing but, as a check, in the routine of production. By such tests, too, may be ascertained the influence upon the efficiency of the whole resulting from wear or other defect in any one component. Compression, lubrication, ignition and carburation of the internal combustion engine involve separate series of analytical tests. With suitable procedure and appliances full analytical tests might be made on seed drills. Simple preliminary tests help to show the relation between fluctuation as found in the seeds deposited on a seed bed and certain features of drill mechanism. In respect of wear and tear, agricultural machinery stands almost alone. Exposed to weather, long periods of idleness, and ever varying working conditions, are problems always facing the maker and user of machines and implements for the farm. Of all the outdoor machines the seed drill has the most delicate task. Drills as found on farms sometimes show considerable wear; some are very old. There appears to be no published evidence by which may be gauged the effect on seed distribution of wear, especially wear of the pinions or gear wheels which drive the barrel. It is probable that suitable demonstrations of the effect of wear in important components would induce users of drills to pay closer attention to renewals and repairs.

The simple tests to be described bear on three aspects of drill action in connection with which fluctuations have been discussed, viz.:

Average seeding over a large area.

Average deposition by the separate coulters.

Deposition by one coulter on separate unit lengths of row.

An 11-coulter cup-feed drill was studied. The diameter of the land wheels was 4 ft. 8 in. so that a velocity of 1 mile per hour corresponds to 6 revolutions per minute. For the pinion (gear) wheel employed 13 revolutions of the land wheel corresponded to 21 revolutions of the barrel. There were 16 cups on each side of each disc of the barrel. The cups of one side of a disc empty into one hopper. Thus the seed deposited on a one-foot length of row would be the contents of about 1·76 cups. To raise the land wheels from the ground the chains of the presser irons were suitably adjusted and the presser lever raised. The drill then rested on its coulters, the land wheels being free. Two Y-props

were placed under the axle bar and the presser lever let down so that the props supported the whole weight. In most of the tests to be described the land wheel from which the barrel drive was taken was rotated at 12 revolutions per minute. This corresponded to a velocity on the land of 2 miles per hour. Other rates of rotation were employed for certain tests as later explained. Uniform rotation of the land wheel was ensured by a time check. For convenience a handle was fixed to one spoke of the wheel. The observer rotating the wheel, signified to another observer with a watch, the moments at which this handle passed two marks on a vertical rod. These marks were opposite the ends of the vertical diameter of the land wheel. Seed was collected in paper bags. The seed tubes of the drill were removed and the bags attached to the delivery spouts. After the specified number of revolutions the seed in every bag was weighed. In determining the number of grains delivered by individual cups, the contents of a cup at the moment of emptying into the hopper were caught in a dessert spoon. The grains were then counted.

It is somewhat difficult to ensure that a drill sows at the rate desired. The trials described in § II (*supra*) are an illustration of this. With a given size of gear wheel, seed distribution may be affected by a number of factors. Some are external as, for example, the size and condition of the seed. Of the internal or mechanical factors state of wear of the gear wheels and size of slide aperture are perhaps of greatest importance. Seed passes from the front compartment (seed box) through the slide apertures to the rear compartment (barrel box) of the box of the drill. Aperture size is controlled by the setting of the slides. The influence of variation of aperture was investigated. Three sizes were employed—half open, three-quarter open, and fully open. The land wheel was rotated at 6 revolutions per minute corresponding to a land velocity of 1 mile per hour. For each aperture size six trials were made. A trial was 13 rotations of the land wheel (*i.e.* 21 rotations of the barrel). The grain delivered from each one of the eleven seed spouts was weighed at the end of every trial. The mean per-spout delivery for each aperture size was thus based on 66 weighings. These means were:

Slide	Half open	Three-quarter open	Fully open
Mean delivery (gm.)	170	190	204

The differences between the means are all statistically significant. A difference of 12 per cent. between half open and three-quarter open is of importance in that it reflects one cause contributing to the difficulty of ensuring the desired seed rate. With the constant shaking to which

a drill is subject in the field the effect of aperture variation might be substantially increased. In practice it is left to the horseman to suit the aperture size to the work. Oats and wheat, for instance, pass at different rates through any given aperture and corresponding allowance must be made. More definite information on the relation between aperture size and rate of seeding would be of value in the adjustment of drills for the various seedings carried out on the farm.

That separate spouts (coulters) of a drill may deliver at different average rates is illustrated by the trials described in § II (*supra*). The drill used in the tests here described showed significant inter-spout differences. It is needless to pause over the magnitude of these differences, but certain features connected with them are of interest. Seed passes into the barrel box through six slide apertures which may be numbered 1–6 from the off to the near side. Each aperture is opposite a compartment (1–6) of the barrel box. On the shaft of the barrel are six discs which rotate in and pick up seed from the compartments. There are 16 cups on each side of a disc and these two sets of cups (referred to as L = left and R = right) deliver into two hoppers and so feed two spouts (coulters). On disc 3 the L cups are not provided with a hopper. The space this hopper should occupy is taken up by the middle partition of the barrel box which carries a bearing for the barrel shaft. The arrangement may be thus represented:

Apertures	6		5		4		3		2		1	
Discs with cup	L 6	R	L 5	R	L 4	R	— 3	R	L 2	R	L 1	R
Spouts (coulters)	11	10	9	8	7	6	—	5	4	3	2	1

In these tests determinations were made not only of inter-spout differences in general but also of differences between the two spouts fed by the same aperture and same disc, *e.g.* 11 and 10 or 3 and 4. These latter differences were relatively small. Briefly, a difference such as 10 and 11 or 6 and 7 was smaller than a difference such as $(10 + 11)/2$ and $(6 + 7)/2$. This suggested that variable flow through the apertures might be one cause of the familiar inter-coulter differences. This flow is presumably governed by two principal factors. Size of aperture is the first. All the slides move together, being operated by a rod on the ends of which are toothed wheels working in ratchets affixed to the barrel box. The satisfactoriness of this device seems open to question. Another factor is the "pressure" of the seed at each aperture. The general trend of the spout data suggested that this pressure was lower for apertures 1 and 6 than for 3 and 4. To test this, apertures 2 and 5 were completely closed so that they no longer shared seed supply with

neighbouring apertures. Delivery from the spouts which continued in operation was naturally increased. The percentage increases were:

For mean of spouts	1 and 2	5 (only)	6 and 7	10 and 11
Percentage increase	28	7·5	5·5	19·1

The differences between these increases are all statistically significant. They indicate that before the closing of apertures 2 and 5 there must have been pressure differences between apertures 1 and 3 and between 4 and 6. Such pressure differences are presumably related to the lateral interval between apertures. In these intervals then, and in exact aperture sizes, are probably some of the causes responsible for the inter-spout differences which have so often been demonstrated.

It remains to discuss drill mechanism in relation to fluctuation in seed distribution from foot to foot along a row. This fluctuation, as a factor in plant development and yield, transcends in importance both working variations in per acre seed rate and inter-spout differences.

Two prominent mechanical causes of such fluctuation suggest themselves. One is inconstant velocity of the drill as it is drawn across the field. The second is fluctuation in number of seeds picked up, from time to time, by any and every cup of the drill.

It is a familiar fact that swift changes in velocity mark the passage of the drill over any but the best seed beds. They are best appreciated by watching the corresponding vagaries of the rotation of the barrel. Horses not pulling together may play a part. One or both wheels may sink in a soft patch with sudden decrease of drill velocity followed by swift acceleration as the horses jerk forward again. Tests were made at 6, 12 and 18 revolutions per minute of the land wheel. These rates correspond to land velocities of 1, 2, and 3 miles per hour. Differences in mean seed delivery were, however, too small to signify in explanation of fluctuation as a result of quick changes in land velocity. Possibly a wider range than 1–3 miles per hour marks the jerks and instantaneous halts of the drill under field conditions. It is impossible, however, to pursue the inquiry further without knowledge of the exact fluctuations in drill velocity associated with practical seeding. An automatic recorder, preferably working on the barrel of the drill, would have to be used.

Data on "cup-load" (number of grains delivered into the hopper by a single cup) were obtained in the way already described. In all, 1100 cup-loads were counted, *i.e.* 6–7 loads from every one of the 176 (16 × 11) cups contained in the drill. Their frequency distribution is given in **Table IX.** It is essential to remember that this table indicates not inter-cup differences but, mainly, fluctuation in the number of seeds

picked up by any and every cup from time to time. Of the causes of load inconstancy of the individual cup more is said later. The standard deviation of the cup-load distribution is $\sigma = 2{\cdot}4$ grains and the mean $M = 11{\cdot}66$ grains. It has been explained that the seed deposited on a foot length of row must be the loads of 1·76 cups. For simplicity let the per-foot seeding be taken as 2·0 cup-loads. Then the mean number of seeds sown per foot should be $2 \times 11{\cdot}66 = 23{\cdot}32$; similarly the standard deviation of number of seeds per foot should be

$$\sqrt{2}.\sigma = \sqrt{2} \times 2{\cdot}4 = 3{\cdot}39.$$

These deductions follow from familiar statistical theory. They may be checked and the frequency distribution of number of seeds per foot forecast from that of cup-loads, by suitable computation. Thus let f_1 = frequency of a cup-load s_1, the total number of cup-loads being n. Then if the frequencies of cup-loads form a normal distribution, the frequencies of seeds per foot represent all the random combinations of cup-loads in pairs. The chance of the first cup of a pair having load s_1 is f_1/n. It may be combined with another load s_1 the chances of the combination being f_1^2/n^2 and the number of seeds per foot being $2s_1$. Similarly loads s_1 and s_2 giving $s_1 + s_2$ seeds per foot, represent a chance $f_1.f_2/n^2$. Working on these lines and making all possible combinations of the frequencies in Table IX, the theoretical distribution of number of seeds per foot is as given in Table X. In this table frequencies are

Table IX. *Frequency distribution of cup-loads.*

Cup-load	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*
Frequency	1	7	7	15	16	47	86	159	154	202	187	101	63	33	14	7	1

Table X. *Distribution of expected frequency (per cent.) of number of seeds per foot on the basis of two cup-loads per foot.*

Number of seeds per foot	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
Expected frequency (%)	0·04	0·11	0·22	0·45	0·73	1·25	1·94	3·10
Number of seeds per foot	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*
Expected frequency (%)	4·65	6·71	8·85	10·98	12·11	11·99	11·07	8·99
Number of seeds per foot	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*
Expected frequency (%)	6·54	4·45	2·74	1·57	0·83	0·38	0·17	0·07

expressed as percentages of the frequency total (this simplifies the table which involves a total of 1,210,000 combinations). Actually, as 3 and 19 are the range limits of single cup-load, the per-foot expectation must extend from $2 \times 3 = 6$ to $2 \times 19 = 38$. But to shorten the table the very low frequencies at both extremes have been omitted. The table contains 99·94 per cent. of the total frequencies. As calculated from the full expected distribution $M = 23{\cdot}32$ and $\sigma = 3{\cdot}39$. These values agree with those deduced above by simple statistical formulae.

The drill employed in these tests was used in sowing field D. There, however, a different pinion and only nine coulters were required for the inter-row spacing adopted. In consequence strict comparison between seed distribution in the field and theoretical expectation cannot be effected. The mean values for seeds per foot were, for field D, $M = 17 \cdot 7$, and on expectation $M = 23 \cdot 2$. In harmony with this difference the theoretical distribution class values as a body are higher than those of the field count. Further, expectation was based on two cup-loads per foot instead of the actual value of 1·76 cup-loads. With these facts in mind, however, a broad comparison may be drawn between theoretical expectation and the field count. The most striking feature this reveals is in general distribution form. The field distribution is less sharply concentrated round the mean value, *i.e.* the distribution is more scattered than that of expectation. In this difference is presumably reflected disturbance of mechanical action induced by the jolting of the drill on the field. The distribution of Table X may fairly be taken to represent the range and nature of fluctuation in per-foot seed distribution for which the drill itself is solely responsible.

Table XI. *Frequency distribution of number of seeds per foot in field D. For comparison with the theoretical expectation of Table X. Frequencies are expressed as percentages.*

Number of seeds per foot	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
Frequency	0·3	- -	0·6	1·2	0·9	2 6	2·6	2·1	3·2	5·6	5·0
Number of seeds per foot	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
Frequency	3·8	7 9	7 6	7·3	8 8	5·3	7·3	3·2	5 3	3·5	2·9
Number of seeds per foot	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*37*	*40*
Frequency	3 2	2·0	0 6	1·5	1·2	2 6	0·3	0·9	0·3	0·3	0·3

A measure of difference between the field distribution per foot and the expectation is afforded by the variance (variance = square of standard deviation). Values of standard deviation for fields D, G, L and P have been given in § III (*supra*). They range—as in seed and plant counts in these and similar experiments—from about 5·0 to 7·0. A value of 6·0 may be taken as representative. It thus appears that:

(i) For fluctuations inherent in drill mechanism combined with those produced by disturbances in drill action in the field ... $\sigma^2 = 36 \cdot 0$.

(ii) For fluctuations attributable solely to drill mechanism $\sigma^2 = 11 \cdot 5$.

It must therefore be inferred that a substantial part of the fluctuation in number of seeds deposited per foot of row, is attributable solely to inherent fluctuations of drill mechanism. These, in their turn, as here measured, result from inconstancy in the cup-load, *i.e.* the number

of grains deposited in the hoppers from time to time by any and every cup of the drill.

Many circumstances affect cup-load. They are of two main kinds —those influencing number of grains picked up and those influencing number lost before discharge into the hopper. Observation of drill action suggests the latter kind as the more important. The load of a cup, mechanically, consists of two parts. In the hemispherical hollow of the cup are grains which disturbances rarely dislodge. Delicately balanced on these is an insecure pile or top-load. Jolts and other disturbances affect the top-load in a most fluctuating manner; this is patent to careful observation. It is suggested therefore that cup design calls for systematic re-consideration. The problem is of great intricacy. To move grains of corn singly or in small regular quantity is a well-known mechanical difficulty. The essence is the subtle intangibility of the corn grain which its peculiar conformation induces. Four new types of drill have recently been produced. Two adopt an adjustable cup of new design; one uses the cups as intermediaries in seed delivery; the fourth, discarding cups, employs a prehensile mechanism. Thus recent trend in design appears to be guided by a recognition of the defect of the familiar cup.

This preliminary mechanical analysis has essayed to deal with but a few of the factors of fluctuation. A full list of recognisable factors would be lengthy. It appears desirable to mention two kinds of fluctuation factor which are commonly overlooked. Condition of seed may be important. Even flow through slide apertures, cup uptake, and cup delivery are affected by bad seed. Important, common, defects are bad hummeling in barley and oats, excess of copper sulphate dressing in wheat, the presence of chobs and weed seeds, and imperfect screening. Wear of components is a second important kind of fluctuation factor. It is probably most serious in the drive pinions; but wear in any component should not be overlooked. One new coulter-iron, fitted in replacement on an old drill, may, for instance, produce marked irregularity.

Any consideration of improved drill design or better maintenance, must have regard to certain weighty matters of practice. A single drill, with two barrels and double-faced cups, is expected to sow all the crops of the farm. Adjustments for seed rate, row interval, and slope of land, are indispensable. The drill must function on the dusty seed beds of spring on light land and the stubborn, cloddy, autumn tilths of the clay. Idle most of the year, it has a long life. While improvements must be consistent with great versatility of action they cannot look for that encouragement from rapid market demand through displacement of old models which stimulates new design in most machine manufacture.

On the evidence so far available, the cup drill must be regarded as mechanically superior to the force feed type. In all drills soundness of material and workmanship have a greater importance than is commonly recognised. Some of the new designs may prove advantageous in this country; at present the English made cup drill appears to be the best type available.

The collection of the extensive data on which this paper rests would not have been possible without the help of Mr L. R. Doughty and Mr C. B. Taylor, Colonial Office Agricultural Scholars, to whom warm thanks are tendered.

SUMMARY.

A regular optimum spacing among plants is the theoretical ideal. Regularity is difficult to secure and the ever varying optimum is not determinable. But earlier investigations have shown that field crops of corn are marked by extremely high fluctuation in population density along the rows of plants; and further, that in this fluctuation lies an important limitation to potential yield. Wider knowledge of this limitation is being sought. The experiments have clearly confirmed plant density fluctuation as a characteristic of field crops (of wheat). Measures of this fluctuation and analyses of its nature and causes are the subject of the paper.

In relation to plant development and yield, fluctuations in density or spacing from point to point along the row, are the most important features associated with drill action. These have been measured by counts, both of seeds and of plants, on unit lengths of row. Such "census" counts are described in detail for four normal fields. Plant counts were made periodically. In general a unit length of one foot of row was adopted. For analytical purposes the refinement of a per-inch count proved necessary.

Fluctuation in seeds deposited per foot may be illustrated by the data from one of the fields. The mean was 18·0 and the standard deviation was 7·2. In aggregate the field could be regarded as consisting of five equal portions (quintiles of the per-foot distribution) for which:

Number of seeds per foot = 5·0–12·2; 12·2–15·0; 15·0–18·0; 18·0–22·3.

Equivalent seeds rates (bushels per acre) = 1·42; 2·00; 2·35; 3·11; 3·70.

The distribution per inch, determined by a specially devised method, is illustrated for two fields in Diagram I. Four equal aggregates (quintiles of per-foot distribution) from one and the same acre had the widely different seedings displayed in Diagrams II and III.

It is difficult to separate the contributions to fluctuation arising from the inherent mechanical action of the drill and from disturbances in

that action which soil variation and tilth irregularity induce. Per-foot and per-inch distributions suggest that seed deposition on these and intermediate lengths of row is almost random. Tests upon this point are described in § V. These show that while seed deposition is not entirely random in a full statistical sense, the bias must be very slight.

Direct influences of soil variation and tilth irregularity should be doubly reflected in the census data. One portion of a marked acre might display higher fluctuation than another. Repeated test gives no indication of such a locality effect. Again seed deposits on adjacent unit lengths should be correlated if soil variation is seriously contributory to fluctuation. Only by indirect inference is a tendency to such correlation demonstrable. This tendency is the slight bias disturbing purely random deposition already mentioned. It is of no practical significance and, effectively, seed deposition by the drill is random. Moreover, it is in the drill rather than the soil that the causes of fluctuation in population density are to be sought.

A preliminary analysis of drill mechanism was made, the drill for this purpose being supported so that the land wheels could be rotated by hand. The outstanding feature proved to be inconstancy of cup-load, *i.e.* number of seeds delivered by any and every cup of the drill into the hoppers. It is shown that, from this cause alone, wide fluctuation in per-foot deposit of seed is inevitable. For counts of seed per foot in the field the standard deviation was about $\sigma = 6{\cdot}0$. Fluctuation in seeds per foot attributable solely to inconstant cup-load was shown to be of the order $\sigma = 3{\cdot}4$. Improvement in cup-design thus appears to be the salient requirement for more constant drill action.

BIBLIOGRAPHY.

(1) Engledow, F. L. A Census of an Acre of Corn (by Sampling). *Journ. Agric. Sci.* **16**, 1926.

(2) A Census of an Acre of Barley. *Journ. Roy. Agric. Soc. Eng.* **87**, 1926.

(3) The Trials of Corn and Seed Drills. *Journ. Roy. Agric. Soc. Eng.* **73**, 1912.

(4) *Journ. Nat. Inst. Agric. Bot.* No. 6, 1927.

(5) Hunter Smith, J. and Rhys Williams, H. A Census of an Acre of Roots. *Journ. Min. Agric.* **34**, August, 1927

(6) Engledow, F. L. Investigations on Yield in the Cereals. II. A Spacing Experiment with Wheat. *Journ. Agric. Sci.* **15**, 1925.

(7) Greenwood, Major and Yule, G. Udny. An Inquiry into the Nature of Frequency Distributions representative of Multiple Happenings with Particular Reference to the Occurrence of Multiple Attacks of Disease or of Repeated Accidents. *Journ. Roy. Stat. Soc.* **83**, Pt. II, 1920.

(*Received September 24th,* 1927.)

THE SLAKING OF DRY SOILS WITH WATER.

By K. T. HARTLEY, M.A., B.Sc. (Oxon).
Imperial College of Agriculture, Trinidad, British West Indies.

Introductory.

It has been urged by Bouyoucos (1) and by Haines (2) that soil granulation is caused by the action of water on lumps of partially dried soil, and it is usually accepted that alternate dryings and wettings are largely responsible for the production of tilth. The work described in this article was undertaken to determine whether measurements of the time required for the complete disintegration by water of lumps of dry soil might furnish a reliable method of soil comparison in accordance with these ideas.

Experimental.

The following method of soil preparation was adopted. A suitable quantity of dry, sifted soil is kneaded with water and brought to the point of stickiness. Blocks 3 in. by 1 in. by 1 in., such as were used by Hardy (3) in his measurements on soil shrinkage, are made from the plastic material. These blocks are cut into 1 in. cubes which are moulded by hand into spheres. The spheres are dried over 50 per cent. sulphuric acid for eight days. Satisfactory replicates may be obtained by this method.

Preliminary measurements were made on five soils representative of different types. Both moist and dry spheres were used. Measurements were made by immersing the spheres in 300 c.c. water in a 400 c.c. beaker and taking the time required for complete disappearance of the spherical shape.

Soils	Times of disintegration: Moist	Times of disintegration: Dry (min.)
1. Lateritic clay soil	Many days	1·5
2. Heavy colloidal clay soil	Very long and indefinite time	25
3. Fine silt soil, high hygroscopic coeff. ...	Very long and indefinite time	30
4. Fine silt soil, low hygroscopic coeff. ...	Very long and indefinite time	22
5. Coarse silt soil	25 min.	14

There are obvious differences between these different types of soil, but the method appears to be too crude for detailed application.

A method at once simple, reliable and generally applicable has proved very difficult to find, and this difficulty has limited the present work to an investigation of the local (Trinidad) alluvial silts. The following list makes brief mention of the methods tested.

1. Sphere made too large to pass the constricted part of a lamp-glass chimney. Time measured for disintegration to proceed far enough for sphere to fall through. Results very erratic owing to unevenness of disintegration. Difficulties not removed by substituting cones for spheres.

2. Sphere made with a central hole and hung in water by a string. Failed owing to the development of cracks from the central hole.

3. Sphere stood on a short length of gas piping in water, either with or without small weights on top. Irregular cracking again troublesome.

4. *Modification of Whittles' vibration method* (1). Sphere held on a wire or cork ring in a bottle whose bottom had been replaced by a celluloid cap, against which the hammer of an electric bell vibrated. This was no improvement on the lamp-chimney method, but probably, as in other vibration methods tried, the stirring effect was insufficient. A more vigorous, but yet standardisable method of agitation, might prove useful, especially for the more colloidal soils whose component particles adhere too strongly to permit of their being treated according to the standard method described below.

5. Sphere held in a funnel with a slow stream of water running through. The apparatus choked with particles of soil and air bubbles.

6. *Standard method.* The sphere is suspended in an open wire basket hanging on a light spring. The extension produced by the sphere is measured, and the time taken for this to fall to a half is noted. The method proved satisfactory for silt soils, and may be applicable to any type of soil whose content of colloidal matter is not great. In the case of highly colloidal soils, vigorous agitation is necessary to shake the flakes out of the basket. The necessary apparatus is easily constructed, and five sets may be operated so as to give replicate readings on each soil at one time. Satisfactory agreement is generally obtained. The mean times are referred to as "times of slaking."

RESULTS AND DISCUSSION.

The figures in the following table are the results of some of the determinations that have been made.

The moisture content at the point of stickiness is included as a measure of colloid content, and the soils are arranged in order of this quantity.

With fall in colloid content, the time of slaking tends to rise to a maximum, and then to fall. There are a few irregularities, and five definite exceptions. If these five are ignored, and the remaining soils taken in groups of three, the mean values of the two soil constants indicate this peculiarity quite clearly.

	Moisture at point of stickiness (% on oven dry soil)		Time of slaking (min.)		
Soil	Actual	Means	Actual	Prob. error	Means
C 36	56·4		13·0	0·21	
WO 8	50·0		?	—	
W 11	48·8		18·8	0·92	
WO 12	48·0		?	—	
W 12	47·9	51	18·6	0·71	17
WO 14	45·4		?	—	
WO 1	44·2		45·0	0·76	
W 14	43·4		23·0	0·52	
W 16	43·2	43	28·8	0·87	32
W 18	42·1		53·6	3·4	
WO 2	41·1		32·6	0·87	
WO 13	39·9		?	—	
WOA 15	39·0	41	28·0	0·21	38
C 13	37 5		55·0	1·9	
WOA 13	35·8		34·0	0·85	
WOA 7	35·2	36	25·6	0·79	38
WOA 5	34·4		23 0	0·56	
WO 10	33·2		?	—	
WOA 11	31·9		23·6	0·65	
WO 4	31·4	32	39·4	0·73	29
WO 7	31·4		31·6	1·2	
WO 6	29·9		17·8	0·40	
WOA 9	29·2	30	12·0	0·32	21
W 17	27·2		16·4	0·82	
WOA 3	26·2		22·4	0·96	
WOA 16	25·4	26	18·2	0·13	17
W 24	23·1	23	9·4	0·45	9

An explanation in accordance with the views of Bouyoucos (*loc. cit.*), may, at this stage, be submitted. It is suggested that, in the case of the soil which exhibits the highest time of slaking, there is a balance between

the pore-space and the colloid content, such that the colloidal matter can swell to its full wet bulk without necessitating any considerable change in volume in the whole mass. Consequently there is little force tending to burst the sphere. On the other hand, sufficient colloid matter is present to prevent particles dropping from the surface of the sphere under the influence of gravity or of fortuitous water currents.

As the proportion of colloid matter increases, the sphere will show an increasing tendency to break by bursting; and as colloid content decreases, an increasing tendency to break by surface disintegration. This argument requires that the soils be closely related, *i.e.* that the nature of the colloid matter, and the size and nature of the mineral particles, be very similar in all comparable cases. It probably holds good for the silty soils in question, because they are known to be of similar type, and to have come from space-limited areas.

Direct evidence has been collected to show that replacement of water by kerosene, which does not swell the colloid matter, prevents the slaking process, and that replacement by alcohol and water mixtures, which permit less complete hydration of the colloidal matter, hinders slaking.

In further support of this suggestion, the course of the process in extreme cases may be described. In the case of the most colloidal soils showing disintegration, the first stage consists in the complete splitting of the sphere into two or three large pieces. These subdivide progressively, and when sufficiently reduced in size, they drop out of the basket. In the case of the least colloidal soils, the process is quite different. Disintegration starts at once by small particles dropping from the surface in a steady stream. This continues until the sphere is completely wasted, and is usually effected without destruction of the original shape.

No explanation of the failure of five soils to break up is offered. A greater content of humic matter in them appeared to be a possible cause, and a consideration of their origin—land only recently changed from cacao to sugar cane—supported this idea. Subsequent determinations of total nitrogen in these five soils and in a selection of the others showed quite conclusively that there was no systematic difference in organic matter content, so that this explanation must be abandoned.

Conclusion.

It has been shown that there is a kind of equilibrium point between colloidal content and pore space, at which the time of slaking is a maximum. This point may prove to be of theoretical significance, but from

the practical point of view, the presence of a "peak" in the colloid-content time-of-slaking curve, renders determinations of the time of slaking an unreliable means of classifying soil-series.

ACKNOWLEDGEMENTS.

This investigation was carried out at the Imperial College of Tropical Agriculture, Trinidad, B.W.I., as part of the requirements for the Associateship of that Institution, and the author wishes to express his gratitude to Prof. F. Hardy for suggesting the problem and for his helpful advice throughout the progress of the work.

REFERENCES.

(1) BOUYOUCOS (1924). *Soil Sci.* **18**, 103.
(2) HAINES (1921). *Journ. Agric. Sci.* **17**, 264.
(3) HARDY (1923). *Journ. Agric. Sci.* **12**, 243.
(4) WHITTLES (1923). *Journ. Agric. Sci.* **12**, 18.

(*Received October 4th*, 1927.)

THE VARIATIONS IN MILK YIELDS CAUSED BY SEASON OF THE YEAR, SERVICE, AGE, AND DRY PERIOD, AND THEIR ELIMINATION.

PART III. AGE.

By H. G. SANDERS, M.A.

Institute of Animal Nutrition, School of Agriculture, Cambridge.

(With Thirteen Text-figures.)

Section A. The Variation of the Total Lactation Yield with Age.

Age, it will be remembered, is here measured in lactations, but little error is involved if the true age in years, at the commencement of the lactation, is taken as two more than the number of the lactation—*e.g.* a cow, on the average, calves her third calf when she is roughly 5 years old.

The distribution of age in these data has already been given and discussed in Part I, and the following points noted:

(A) A large proportion of young cows calve from August to December.

(B) The S.P., on the average, is long for the 1st lactation, short for the next three, and lengthens again for older cows.

(C) The mean D.P. before the 2nd lactation is shorter than normal.

In an attempt to ascertain how the lactation yield varies with age, these three facts must be taken into account; furthermore, the age distribution showed that the average length of a cow's milking life is only 3·27 lactations—*i.e.* a number are culled; it is probable that some of these are discarded as poor producers, and consequently the older cows included, are, to a certain extent, selected animals.

A correlation table between age and "raw" lactation yield gave the mean yields for the different ages represented in Fig. 23, where these yields are given as percentages of the 1st lactation yield; by this method no allowance is made for (A), (B) and (C) above and all the lactations are "lumped" together, no account being taken of the fact that selection has been going on.

It will be seen that there is a definite relation between these two

variables, the yield rising at first, and then declining; this suggested a curve of the form shown, the equation of which is

$$y = 10^{\{1 \cdot 9384 + \cdot 0467a - \cdot 00276a^2 - \cdot 000027a^3\}},$$

when $\quad y =$ total lactation yield,

and $\quad a =$ age in lactations.

The curve cuts well through the points obtained, and by differentiation the highest point was found to occur when $a = 7 \cdot 65$—*i.e.* the maximum output is reached at a little over $9\frac{1}{2}$ years of age.

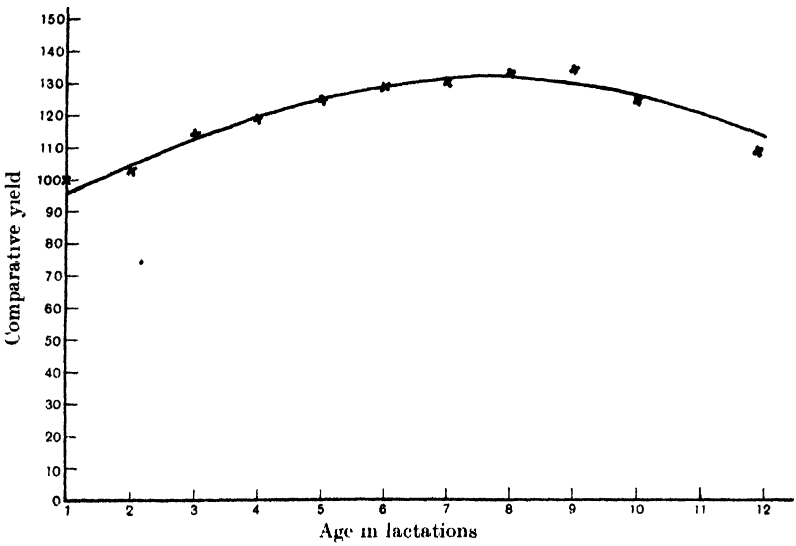


Fig. 23. Variations of total lactation yield with age.
Raw lumped lactations.

This curve shows how the yields of all the recorded cows in Norfolk are dependent on age, but cannot be considered as a true representation of the underlying physiological function, and does not provide a sound basis for the estimation of a cow's yield at one age, from her yield at another; to obtain this allowance must first be made for any selection that may be practised.

The data contained the first 1, 2, 3, 4, 5 or even 6 lactations of some cows, the 5th, 6th and 7th of others and so on, and hence, to find the variation of individual cow's yields with age, a composite curve had to be built up The records contained the 1st and 2nd lactations of 430 individuals, and the means were 6177 lb. for the 1st lactation and 6381 lb. for the 2nd; putting the 1st lactation yield at 100, these same cows

averaged 103·3, then, in the 2nd lactation; similarly there were 375 cows with lactations 2 and 3, giving means of 6554 lb. and 7213 lb. respectively; if the former is equivalent to 103·3, the latter corresponds to 113·7, the comparative yields for lactations 1, 2 and 3 being 100·0, 103·3, 113·7; in this way the curve was built up all through, some cows dropping out, and others coming in at each step.

The actual distributions are not given, as this curve is only an intermediate stage in the elimination of factors, other than age, operating, but the figure arrived at is shown in Fig. 24, and will be seen to fit the means obtained closely; the equation of this curve is

$$y = 10^{\{1\cdot9502+\cdot0379a-\cdot00107a^2-\cdot000175a^3\}}.$$

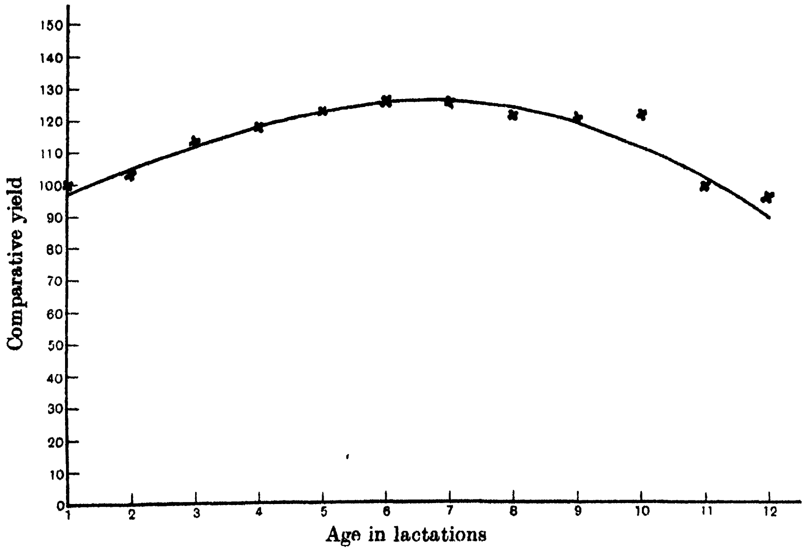


Fig. 24. Raw lactations of individual cows.

The fall in yield with older cows is noticeably greater here, where the effect of selection is eliminated, and the maximum is reached at $a = 6\cdot70$, as against $a = 7\cdot65$ in Fig. 23.

The result however is still subject to (A), (B) and (C) above; the last could not be allowed for at this stage, because the effect of the length of the D.P. on the next lactation had not been found, but (A) and (B) could be, and were, allowed for by means of the corrections already obtained for Month of Calving and S.P.

From the yields corrected individually another composite curve was built up; the distributions are shown in Table XX, and the means at the

foot of that table are shown in Fig. 25, together with the fitted curve the equation of which is

$$y = 10^{\{1{\cdot}9381 + {\cdot}0610a - {\cdot}00584a^2 + {\cdot}000071a^3\}}.$$

The curve gives a very good fit to the data and of the first 8 points, only the second deviates to any great extent from it; it seems impossible to doubt that the comparative yield for the 2nd lactation is low, because of (C)—the short D.P.'s before this lactation have not been corrected for; even at the later ages when the numbers of lactations are greatly

Fig. 25. Variation of total lactation yield with age. Corrected yields of individual cows.

reduced, the means lie surprisingly close to the curve. The maximum is reached by this curve when $a = 5{\cdot}90$ lactations.

In Fig. 26 the three curves, whose fit and method of calculation have been shown, are put on the same scale for comparison.

The figure obtained by taking the uncorrected yields of individual cows (dotted line) keeps below the curve from raw lumped lactations (broken line) all through; here then is a definite view of the amount of selection that is being practised in the herds of Norfolk—it is just apparent from the outset and gradually becomes more intensive until, from the 6th lactation onwards, it leads to a very different type of variation in yield with age. It appears, therefore, that only a small proportion of cows are discarded because of low yields until the 5th or 6th

Table XX. *Variation of Yield with Age—Individual Cows, Corrected Yields.*

Total Lactation Yield in lb.	Lactation Number 1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9	10	10	11	11	12
2,000– 2,499	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
2,500–	2	3	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
3,000–	10	3	7	.	1	1	.	1	.	.	.	.	.	1	.	.	.	.	.	.	.	.
3,500–	19	14	10	3	2	2	2	1	1	1	.	.	.	.	.	.	.	.	.	.	.	.
4,000–	26	24	13	8	10	5	3	3	3	1	2	2	.	1	.	1	.	.	.	.	.	.
4,500–	30	39	26	9	11	12	8	8	3	1	2	4	1	2	1	1	.	.	.	.	.	.
5,000–	50	36	36	32	26	15	14	6	2	3	.	3	3	2	.	.	.	.	.	1	.	1
5,500–	56	48	46	30	33	24	15	15	6	4	5	4	3	1	2	2	.	.	.	1	.	.
6,000–	56	51	40	38	34	41	18	24	13	11	9	6	5	7	1	.	.	.	.	1	1	1
6,500–	57	45	40	52	45	36	34	15	13	14	11	13	7	3	3	2	1	2	1	.	.	.
7,000–	41	38	44	37	27	36	24	29	14	18	13	8	4	9	2	4	3	.	1	1	.	.
7,500–	33	42	31	38	28	30	23	22	24	18	15	17	6	5	.	3	1	2	1	1	1	.
8,000–	17	27	23	36	30	34	31	27	20	16	10	13	5	4	2	2	.	4	1	.	.	.
8,500–	12	28	23	27	24	23	12	21	7	16	11	12	6	9	4	1	4	3	1	.	.	.
9,000–	9	9	11	21	19	13	7	11	9	9	7	8	3	3	1	2	1	.	.	.	.	.
9,500–	5	5	4	14	10	14	10	18	7	6	7	5	6	3	1	1	2	1	.	.	.	.
10,000–	3	6	8	9	7	12	3	7	5	7	6	6	2	3	1	2	1	1	1	.	.	
10,500–	3	5	5	5	2	7	7	6	6	5	4	4	2	3	3	2	.	.	.	1	.	.
11,000–	.	1	2	2	3	5	3	2	2	1	.	3	5	1	.	.	.	.	.	.	.	
11,500–	.	2	1	5	5	3	3	3	1	5	4	1	1	2	.	.	.	.	.	.	.	.
12,000–	.	2	1	3	2	2	.	.	1	.	1	1	1	1	.	.	.	.	.	.		.
12,500–	.	.	1	1	.	4	1	1	1	1	2	.	.	.	1	.	.	.	.	.		
13,000–	.	1	1	3	2	1	2	.	.	1	1	.	.	.	1	.	.	.	.	.		
13,500–	.	.	.	1	.	.	1	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.
14,000–	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.
14,500–	.	.	.	1	.		.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
15,000–	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.
15,500–	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.		.	.
16,000–	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
16,500–16,999	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.
Nos. included	430		375		321		221		139		111		60		23		13		6		2	
Means ...	6226 ±50 lb.	6593 ±57 lb.	6711 ±62 lb.	7437 ±64 lb.	7253 ±67 lb.	7575 ±71 lb.	7526 ±82 lb.	7748 ±80 lb.	7926 ±105 lb.	8156 ±101 lb.	8286 ±125 lb.	8052 ±117 lb.	8233 ±163 lb.	8000 ±168 lb.	8498 ±292 lb.	7902 ±249 lb.	8481 ±203 lb.	8327 ±179 lb.	8167 lb.	7167 lb.	7000 lb.	5750 lb.
Diff. between Means ...	+367 ±76 lb.	+5·9 % ±1·2 %	+726 ±89 lb.	+10·8 % ±1·3 %	+322 ±98 lb.	+4·4 % ±1·4 %	+222 ±115 lb.	+2·9 % ±1·5 %	+230 ±146 lb.	+2·9 % ±1·8 %	−234 ±171 lb.	−2·8 % ±2·1 %	−233 ±234 lb.	−2·8 % ±2·8 %	−596 ±384 lb.	−7·0 % ±4·5 %	−154 ±351 lb.	−1·8 % ±4·1 %	−1000 lb.	−12·2 %	−1250 lb.	−17·9 %
Comparative Yield	100·0	105·9	105·9	117·4	117·4	122·6	122·6	126·2	126·2	129·9	129·9	126·2	126·2	122·6	122·6	114·0	114·0	111·9	111·9	98·2	98·2	80·7

1 Cow: 13th Lact., 8803 lb.; 14th Lact., 4868 lb.

lactation; the large number that disappear from the records at an early age must be culled on the score of appearance, etc., but it is very plain, that, in general, only picked animals are retained after maturity has passed.

When the length of the S.P. is allowed for (and, incidentally the Month of Calving—a small factor in comparison) the yields for lactations 2–5 or 6 are materially increased, as, of course, must necessarily be the case, and we arrive at a rounder curve, showing a greater increase for the first few lactations.

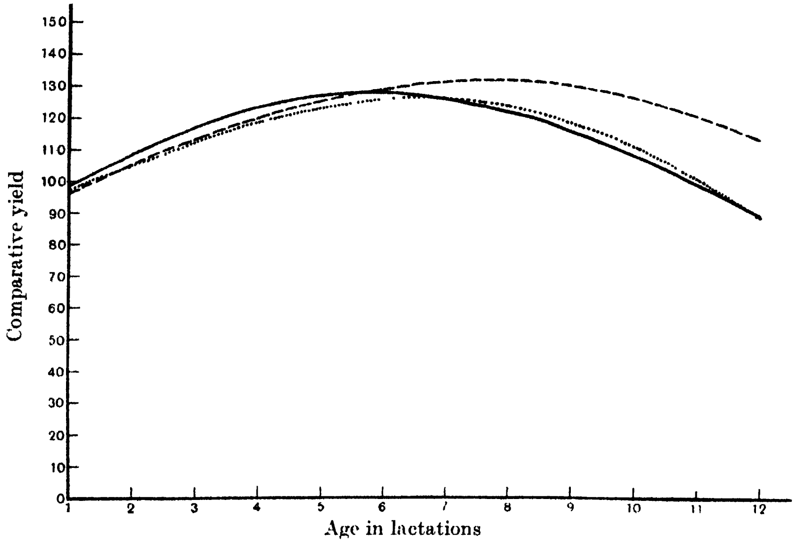


Fig. 26. Variation of total lactation yield with age.

As found from raw lumped lactations - - - - - -
As found from raw lactations of individual cows . . . . . .
As found from corrected lactations of individual cows ——— ———

The comparison of the curves emphasises the weakness inherent in finding the age variation in milk flow by the "raw lumped lactation" method; the error introduced is at no stage negligible, and for the later ages is so great as to impair very seriously the accuracy of the result.

It seems justifiable to conclude that the physiological effect we are here seeking is correctly represented by the continuous curve in Fig. 26; it will be seen that as age increases the milk flow increases until the 6th lactation, and after that decreases at almost exactly the same rate, the yield with the 11th calf being just about the same as with the 1st.

By taking breeds separately the results shown in Figs. 27 to 30 were

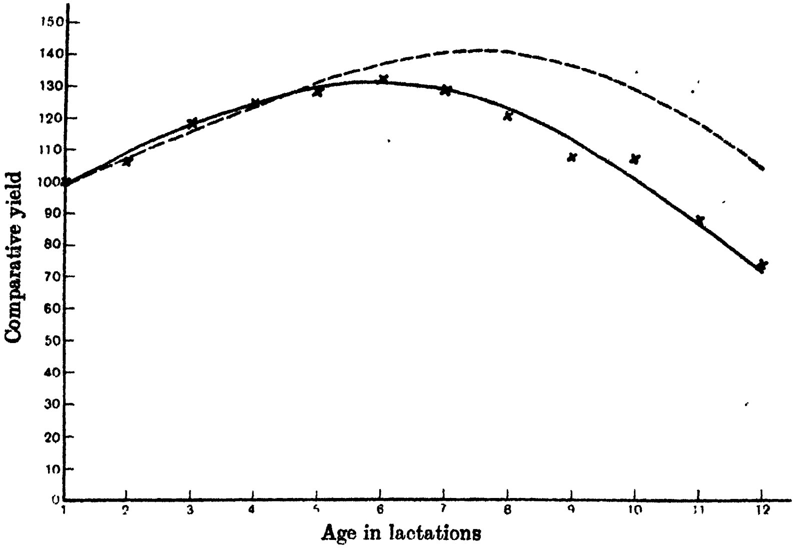


Fig. 27. Variation of total lactation yield with age.

Mongrels {Raw lumped lactations - - - - -
{Corrected yields of individual cows ——— × ×

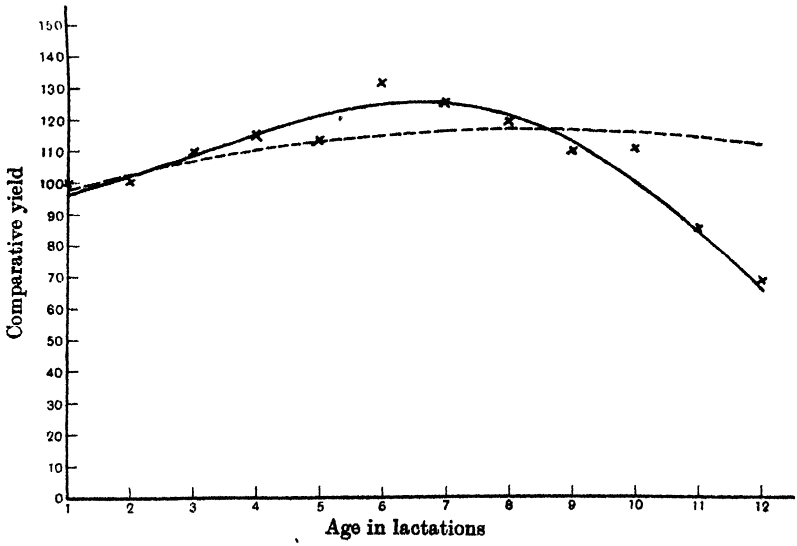


Fig. 28. Variation of total lactation yield with age.

Red Polls {Raw lumped lactations - - - - -
{Corrected yields of individual cows ——— × ×

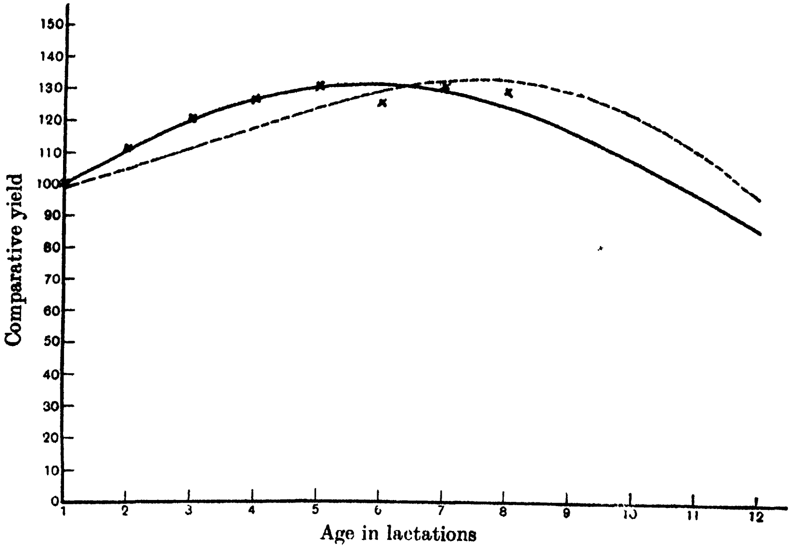


Fig. 29. Variation of total lactation yield with age.

Lincoln Reds {Raw lumped lactations - - - - -
Corrected yields of individual cows ——— × ×

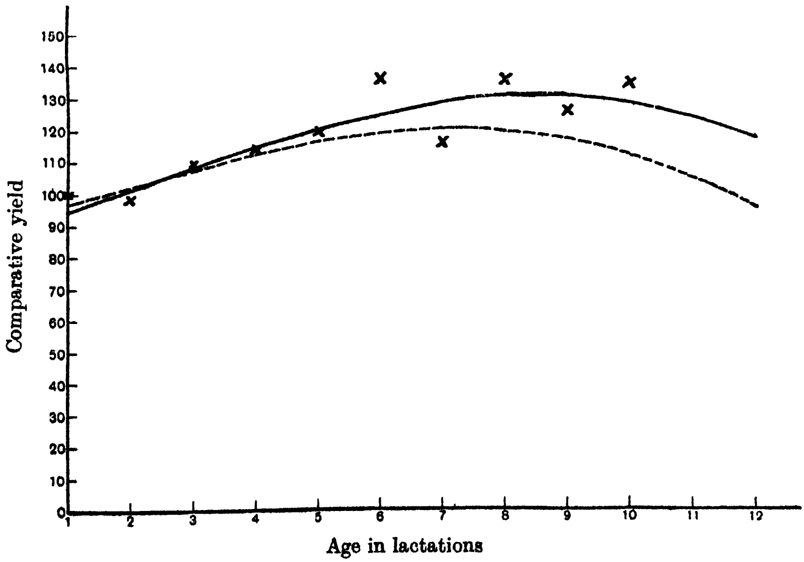


Fig. 30. Variation of total lactation yield with age.

Friesians {Raw lumped lactations - - - - -
Corrected yields of individual cows ——— × ×

obtained; in each case the continuous line represents the curve fitted to the points obtained (small crosses) by the method of building up the curve from individual cow's corrected yields, and the broken line the curve found from the raw correlation between age and yield.

The equations of the curves in Figs. 27–30 are given in Table XXI, together with the value of a giving the maximum value of y.

Table XXI. *Fitted Curves for Variation of Total Lactation Yield with Age.*

Breed	Raw Lumped Lactations Equation of curve, $y =$	Max. when $a =$
Mongrels	$10^{\{1\cdot9553+03812a+\cdot00022a^2-000251a^3\}}$	7·37
Red Polls	$10^{\{1\,9652+\cdot02600a-00176a^2+\cdot000011a^3\}}$	7·88
Lincoln Reds	$10^{\{1\,9710+01935a+\cdot00301a^2-\cdot000379a^3\}}$	7·55
Friesians	$10^{\{1\cdot9587+\cdot02594a-000006a^2-000170a^3\}}$	7·16

Breed	Corrected Yields of Individual Cows Equation of curve, $y =$	Max. when $a =$
Mongrels	$10^{\{1\,9451+05280a\cdot00293a^2-\cdot000180a^3\}}$	5·85
Red Polls	$10^{\{1\,9629+\cdot01656a+\cdot00433a^2-\cdot000566a^3\}}$	6·58
Lincoln Reds	$10^{\{1\cdot9440+06142a-00546a^2-\cdot000020a^3\}}$	5·88
Friesians	$10^{\{1\cdot9422+\cdot03390a-00062a^2-000112a^3\}}$	8·37

y = Total Lactation Yield in lb.
a = Age of the cow in lactations.

Mongrels show a variation very similar to that for all cows; selection plays an important part, but is masked in the earlier lactations by the S.P. variation; the curve for corrected yields of individual cows strikes well through the points given by the data; the fall in yield for the later lactations is very steep.

Red Polls do not follow the same path entirely; the continuous curve gives a very fair fit to the data, only two points (5th and 6th lactations) lying far from it, on opposite sides; selection is apparent from the 9th lactation onwards, but the figure from raw lumped lactations is distinctly abnormal. Possibly the explanation of this may lie in the point to be made in Part IV, that these Red Polls are a very mixed lot as regards milk production, some herds showing extremely good averages, whilst others lie at the other end of the range, selection for beef apparently being practised in some herds, and for milk in others; it may be that under these circumstances the numbers were insufficient to give an even distribution of different grades of cows throughout; by taking each cow as a "control" to herself however, as is done in the other method, the data give a very reasonably smooth set of points.

Lincoln Reds, despite the few records, give a very clear result; the first five points lie almost exactly on the curve and there is plainly a decline for the later ages; the actual rate of decline of this fitted curve is greater than normal, but it is obvious that the means are too scattered to allow of much reliance being placed on this. As before, selection is masked to begin with, but the intermediate curve (not given), for raw yields of individual cows, showed it plainly from the 3rd lactation onwards.

As regards Friesians one of two conclusions must obviously be drawn—either the form of this relationship must diverge markedly from normal for this breed, or enough records have not been obtained to give it accurately; in view of the scattered means from the 5th lactation onwards (where the abnormality is greatest) the latter view seems the most reasonable to take. If the curves mean anything it would seem that negative selection for milk yield is being practised in this breed; this seems improbable unless it arises as the outcome of a positive selection for percentage of butter-fat, or for the more dual-purpose type, or by the loss of the best milkers through udder trouble, etc.

Maturity, or the maximum yield, is reached by Mongrels and Lincoln Reds at the 6th lactation; Red Polls increase a little further (0·2 per cent.) at the 7th, but this may not be considered definite; the Friesian curve does not attain its maximum until the 8th lactation, but, as has been pointed out, this must be taken with extreme reserve.

Table XXII gives the corrections for age calculated from the curves for the different breeds and All Cows and also the Penrith results; the standard has been taken as maturity in each case, and the percentages given are those to be added on to the yield in the various lactations to estimate the yield at the prime.

Table XXII. *Corrections for Age.*

	Percentage to add to estimate the "Mature" Yield					
Age	Mongrels	Red Polls	Lincoln Reds	Friesians	All Cows	Corresponding figures from the Penrith data
1st Lactation	+32·7	+30·0	+32·0	+38·4	+30·6	+30
2nd „	+19·5	+22·6	+18·9	+28·7	+18·0	+18
3rd „	+11·0	+15·0	+ 9·8	+20·5	+ 9·3	+10
4th „	+ 4·6	+ 8·3	+ 3·9	+13·7	+ 3·7	+ 4
5th „	+ 1·0	+ 3·2	+ ·8	+ 8·2	+ ·7	.
6th „	.	+ ·2	.	+ 4·1	.	.
7th „	+ 1·9	.	+ 1·5	+ 1·4	+ 1·4	.
8th „	+ 7·0	+ 3·3	+ 5·6	.	+ 4·8	.
9th „	+16·2	+11·4	+12·3	+ ·2	+10·4	.
10th „	+31·0	+26·3	+22·2	+ 2·2	+18·5	.
11th „	+53·3	+51·9	+35·9	+ 6·1	+29·4	.
12th „	+87·0	+95·0	+54·6	+12·2	+43·7	.

On the whole it does not seem advisable to recommend the use of different sets of corrections for different breeds; it is not at all impossible that there may be some breed peculiarities in this respect but it can hardly be claimed that any have been definitely established. Friesians reach maturity two lactations later than others, according to these figures, and there may well be a true deviation from normal in this supposedly late-maturing breed; on the other hand, it seems doubtful if Red Polls are, in reality, longer in reaching their prime for milk production than Shorthorns. Under these circumstances it is safer to use the figures obtained from All Cows, remembering that there may be breed differences involved, which future research may bring to light; nor should it be forgotten that the use to which these corrections might profitably be put is their application to the yields of individuals, and it is fairly certain that there is more variation (at any rate in this respect) between individual cows of the same breed, than from breed to breed. In each case the mean yields of a number of cows show very much the same variation, and anyone unfamiliar with records might assume that it is a hard and fast rule; this, of course, is far from being the case, individuals showing much divergence in this respect, some, for instance, never equalling in later life their performance as heifers.

In reporting the work on the Penrith data, a table was given comparing the results of many other workers who have studied this question; very good agreement, considering the great variety of breeds, conditions and methods of research, was found. Three others might here be mentioned—those of Gowen (1), Turner (2) and Zwagerman (1).

Gowen's results showed a maximum at 8½ years old for Advanced Registry Friesians, and the corrections for ages of 2½ and 3 years were + 36·5 and + 28·2 per cent.—agreeing admirably with that for 1st lactation above; for an age of 13 years, though, his figure was + 17·5 per cent. as opposed to that of + 29·4 per cent. for the 11th lactation here.

Turner with Guernseys found a maximum at 7–8 years with a correction of + 31·3 per cent. for cows from 2–2½ years old, and, again, only + 16·2 per cent. for ages from 13–13½ years.

These two workers used the "raw lumped lactation" method, and consequently get a very different variation for the later ages.

Zwagerman quoted results from Friesians obtained from the same cows throughout, that gave the following corrections:

1st lact.	+ 57·7 %	4th lact.	+ 7·5 %
2nd „	+ 33·5 %	5th „	+ 1·4 %
3rd „	+ 16·3 %	6th „	+ 0·2 %

maturity being reached at the 7th lactation; these cows calved for the first time at about 2 years old, and consequently the 2nd lactation in these records corresponds in actual age, roughly, to the 1st lactation in these; remembering this, the agreement is fairly good, and this serves to emphasise, what is usually believed to be the case, that it is not the number of lactations a cow has had, which determines this variation, but the number of years she has lived.

For practical purposes the corrections for the early ages are the important ones—by the time the cow is 10 years old the owner usually has a fair idea of her capabilities. It has been claimed that the method of building up a curve from the corrected yields of individual cows gives the true physiological function, but perhaps the variation for the later ages might be more accurately described as pathological; to say that the decline is due to senility is merely a terminological method of evasion, for senility is an ill-defined word; in the heavy yielding cow at least it embraces a number of changes which are really pathological—udder, digestive troubles, etc. Many individuals do not fall off to anything like the same extent after their prime, presumably because they have escaped the maladies usually associated with these ages. The curve shown in Fig. 25, therefore, estimates the yield a cow will give in old age, if she lives long enough, taking into account the probability of the occurrence of the pathological conditions that constitute senility.

HIGH AND LOW YIELDERS.

In attempting to ascertain if what has been said applies equally to High and Low Yielders, the method of building up a curve from individual cows' corrected yields, which has been shown to be the most (in fact, the only) satisfactory one, was found to break down utterly; this arises as a result of splitting the data. It will be realised that no yield can be corrected to give an absolutely exact value to the animal as a milk producer; colds, digestive troubles and such like, often too trivial to be entered in the register, and the variability in the shape of the curve (which in any simple system of correction is bound to introduce error) all tend to preclude the exact estimate of a cow's worth from one or even two lactations, and it will be shown in Part IV that after every correction has been made there is a probable error of 7 or 8 per cent. in the final figure.

For instance, from the curve in Fig. 25, a heifer giving a corrected yield of 6000 lb. in the 1st lactation should give corrected figures of 6640, 7166, 7553 in her 2nd, 3rd and 4th, but obviously no individual

would do so exactly; suppose that this cow was just at the junction between High and Low Yielders and that whilst conforming normally to the age variation, minor factors and imperfect corrections gave her corrected totals of 5600, 7000, 6700 and 8000 lb.—all fluctuations about her mean level well within the usual variation; her increase from the 1st to the 2nd lactation is + 25 per cent., from 2nd to 3rd – 4 per cent., from 3rd to 4th + 19 per cent., and by the division her 1st and 3rd lactations would have to be taken as those of a Low Yielder and her 2nd and 4th as those of a High Yielder—*i.e.* the + 25 per cent. and + 19 per cent. would occur among the Low Yielders and the – 4 per cent. among the High Yielders. It is obvious that at every step this sort of thing is likely to happen and with all the cows on the border line (a considerable proportion) all the big increases would appear among the Low Yielders and the small increases or decreases among the High Yielders—simply and solely because of the fluctuations that are bound to occur, and because a downward deviation, which on the average will be followed by an upward one, would place her among the Low Yielders and *vice versa*; where all cows are included these fluctuations are of course obliterated, but when the data are split into two (or more) parts, they are biassed in different directions for the opposite groups.

The method adopted gives a good example of this; there were in the data the records of the first four lactations of 84 cows of all breeds; these were first of all divided into two groups of 42 each according to the corrected yield in the 1st lactation; the mean yields for the four lactations of these two groups are shown in Table XXIII and Fig. 31.

Table XXIII. *Variation of Yield in first four lactations of High and Low Yielders—84 Cows—divided into two groups according to the corrected 1st Lactation Yield.*

	High Yielders		Low Yielders	
	Mean Yield (corrected)	Mean as percentage of 1st Lactation Yield	Mean Yield (corrected)	Mean as percentage of 1st Lactation Yield
1st Lactation	6845 lb.	100·0	4595 lb.	100·0
2nd ,,	7488 ,,	109·4	5976 ,,	130·1
3rd ,,	8024 ,,	117·2	6667 ,,	145·1
4th ,,	8190 ,,	119·6	6905 ,,	150·3

In the 4th lactation this High Yielding group averaged approximately 20 per cent. more than in the 1st lactation, whereas the Low Yielders averaged 50 per cent. more; a large part of this difference however must

be attributed to the division of the data. The Low Yielders contain not only the really inferior cows, but also those on the borderline that for some cause or other fluctuated about their true level in a downward direction during the 1st lactation; these latter naturally show an abnormally great increase in the succeeding milking periods, which is not compensated for by those that fluctuated in an upward direction in the 1st lactation, because the latter fall in the High Yielders. Obviously

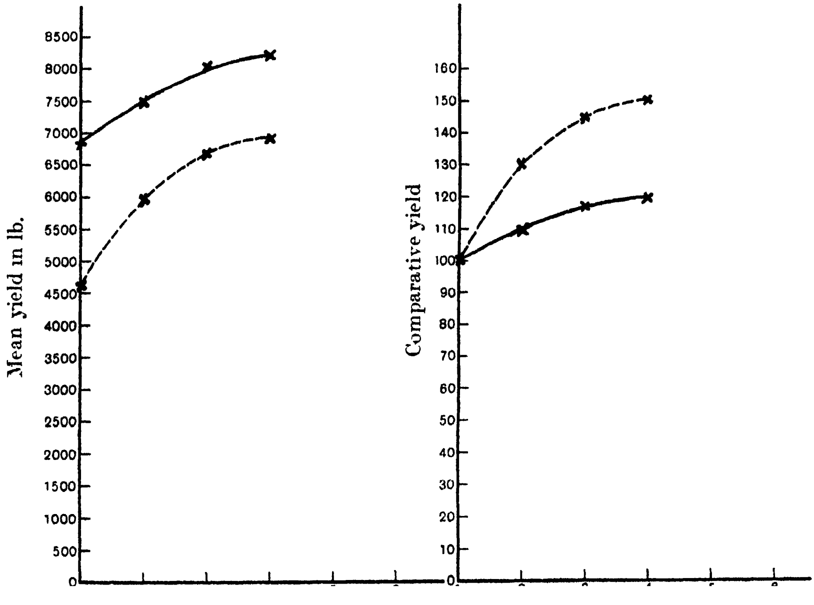


Fig. 31. Mean yields in lactations 1–4 of 84 cows, divided into two equal groups according to the 1st lactation yield (corrected for S.P. and month of calving).
High Yielders ———— Low Yielders - - - - - -

the only method of surmounting this obstacle is to divide the cows into two groups, not on the basis of the 1st lactation yield, but on that of their true level, as given by the yields in all four lactations. In this way two groups of 42 cows each were obtained such that the mean corrected yield in lactations 1–4 of each cow in the High Yielders was higher than the corresponding mean of any in the Low Yielders; the means given by these two groups are shown in Table XXIV and Fig. 32.

The Low Yielders still show a slightly greater increase but nothing like so much difference is seen as before; here the rise from the 1st to the 4th lactation is a little less in actual pounds and a little more as a

percentage. It will be seen that the divergence starts at the 3rd lactation, the rise in the comparative yields from the 1st to the 2nd lactation being just the same in each group. Possibly after that stage the superior cow's ability is prevented from its full expression by limiting factors (nutritional or physiological) which do not obtain in the case of the inferior animal. In too many herds all cows are still fed very much

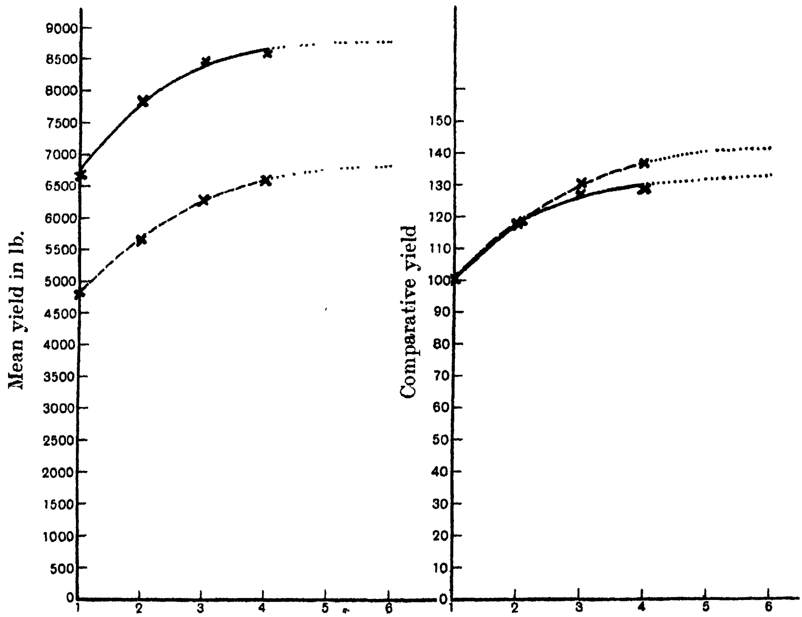


Fig. 32. Mean yields in lactations 1–4 of 84 cows divided in two equal groups according to the average corrected yield in these four lactations.
High Yielders ———— Low Yielders - - - - - -

Table XXIV. *Variation of Yield in first four Lactations of High and Low Yielders—84 Cows—divided into two groups according to the mean corrected Yield in Lactations* 1–4.

	High Yielders		Low Yielders	
	Mean Yield (corrected)	Mean as percentage of 1st Lactation Yield	Mean Yield (corrected)	Mean as percentage of 1st Lactation Yield
1st Lactation	6643 lb.	100·0	4798 lb.	100·0
2nd ,,	7810 ,,	117·6	5655 ,,	117·8
3rd ,,	8429 ,,	126·9	6262 ,,	130·5
4th ,,	8536 ,,	128·5	6548 ,,	136·5

alike irrespective of yield and it might be that this system has held back a proportion of the High Yielders, when they would otherwise have gone on increasing; careless rationing is rapidly passing and it may be that where every cow is fed according to yield the age variation is the same for high and low producers.

It is not asserted that this is the explanation of the above difference, but only suggested that it is a possible one; the curves showing the comparative yields in Fig. 32 certainly point to some limiting factor as operating on High Yielders, and it is to be hoped that, if this factor is a nutritional one, more modern methods of feeding will eliminate it. For this reason, because of the complications that would be introduced into an otherwise simple method of standardisation and because the small numbers available would not allow of great accuracy, no separate corrections are given; it is clear that both groups conform fairly well with the variation shown by all cows, and it need only be remembered that under the conditions obtaining when these records were made High Yielders did not increase quite so much as they approached maturity as did Low Yielders. A heifer with a low yield may increase abnormally afterwards, because her 1st lactation may have been a deviation below her real level, and similarly one with a high yield in her 1st lactation may not increase so much, but the possibility of these deviations is, of course, included in the probable error of the final estimate which is given and discussed in Part IV.

SECTION B. VARIATION IN THE SHAPE OF THE LACTATION CURVE WITH AGE.

In finding and measuring the effect of any factor that influences milk yield the Total Lactation Yields are sufficient, but if it is required to go any distance towards explaining the variations found, the only path that can be followed with hope of success is that by way of mean lactation curves; we have seen that season and service each have a very definite effect on the shape of the lactation curve, and here the question of how the shape varies according to the age of the cow is discussed.

In this we have one advantage in that we may (in fact, must) consider the successive lactations of particular cows; not only does this procedure lessen the necessity for a very large number of records, as individual peculiarities are "controlled", but also, since on the average a cow produces calves at intervals of approximately a year, it means that the distributions of the month of calving will be very much the same

throughout, thus obviating the need for correction for this factor; the curves given below have not been corrected in any way.

Restricting the work to Mongrels, these were

36 Cows with lactations 1, 2, 3 and 4,
33 „ „ 5, 6 and 7,
26 „ „ 7 and 8.

These were copied out again on to separate sheets and the mean lactation curves worked out; in any comparison it must be remembered that there are two distinct breaks in the series, and the shape of one of the curves can only reasonably be compared with that of one of the others given by the same group of cows.

Table XXXIII gives the distributions of the Month of Calving in these lactations, together with the mean S.P.'s and Total Lactation Yields; the average curves are shown in Figs. 33–35.

Table XXV. *Month of Calving Distributions, etc. of Lactations included in Curves* (Figs. 33–35).

	A Group—36 Cows				*B* Group—33 Cows			*C* Group—26 Cows	
Month of Calving	1st Lact.	2nd Lact.	3rd Lact.	4th Lact.	5th Lact.	6th Lact.	7th Lact.	7th Lact.	8th Lact.
January	.	1	1	7	4	3	5	4	3
February	3	6	5	4	6	6	6	2	8
March	5	4	5	5	1	4	2	3	2
April	4	1	1	2	1	1	2	2	.
May	1	4	3	1	3	1	1	1	.
June	6	2	1	.	2	.	2	.	1
July	.	.	2	3	2	3	2	2	3
August	.	5	1	.	1	2	1	1	3
September ...	6	3	1	1	3	3	2	2	1
October	6	5	5	5	2	3	3	1	2
November ...	4	3	6	5	3	2	4	4	.
December ...	1	2	5	3	5	5	3	4	3
Total ...	36	36	36	36	33	33	33	26	26
Mean S.P. (days)	85·6	72·8	77·8	76·2	83·4	79·2	84·0	105·9	114·8
Mean Total Lactation Yield (lb.) (uncorrected)	5783	6331	7138	7374	7919	8448	7958	9882	9353

The distributions of Month of Calving are fairly similar for the different lactations of the same group of cows, but considerable difference exists from group to group; the same applies to the mean S.P.'s—except in *A* Group where the mean is about 10 days higher for the 1st lactation than for the others. The mean Total Lactation Yields conform very admirably to the normal variation, but it is very clear that *B* group contains better cows than *A* group, and *C* group distinctly superior ones to the other two—a surprising agreement with the incidence of selection that has already been noted.

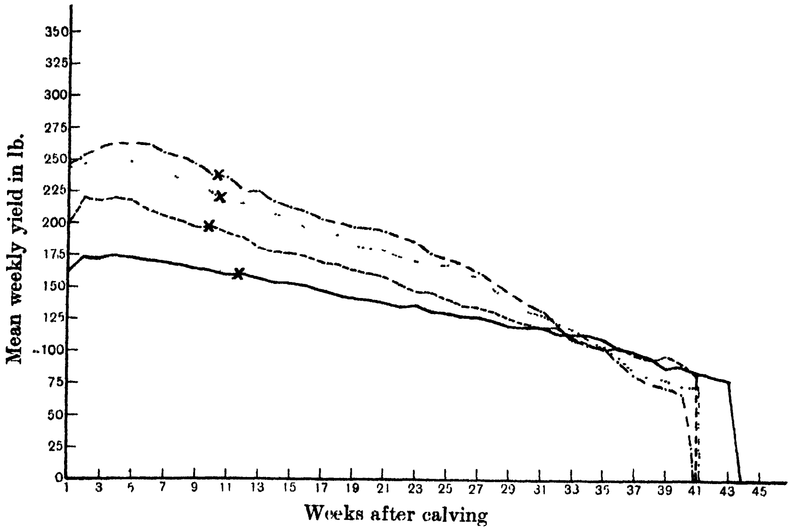


Fig. 33. Mean curves for lactations 1–4 of 36 cows (Mongrels).
1st lactation ——— 2nd lactation - - - - - 3rd lactation • • • • •
4th lactation - · - ·- Time of service ×

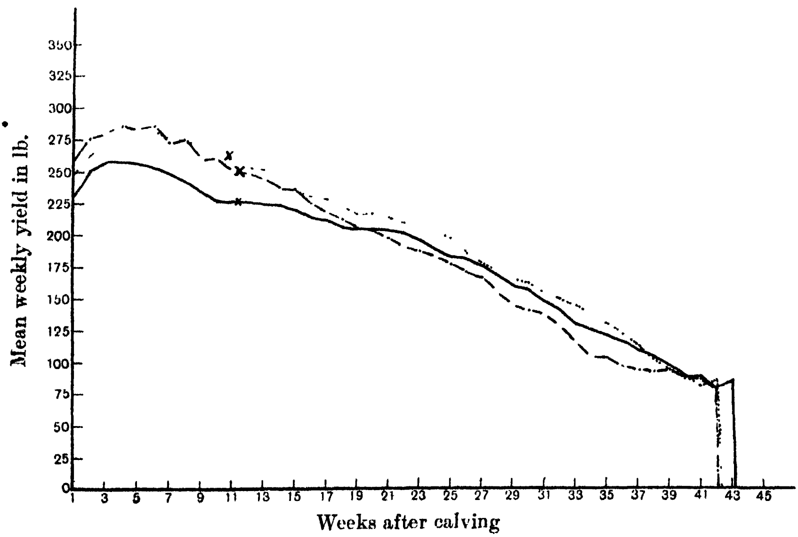


Fig. 34. Mean curves for lactations 5, 6 and 7 of 33 cows (Mongrels).
5th lactation ——— 6th lactation • • • • • 7th lactation - - - - -
Time of service ×

Table XXVI. *Comparison of Lactation Curves for Different Ages.*

	Comparative Yield from the smoothed variation for All Cows (Fig. 25)	Comparative Total Lactation Yield of these Cows	Comparative Average Yield during weeks after Calving 1–10	11–20	21–30	31–40
A Group (36 Cows)						
1st Lactation	100·0	100·0	100·0	100·0	100·0	100·0
2nd "	110·7	109·4	123·3	117·1	108·3	99·6
3rd "	119·4	123·4	143·5	133·1	124·5	95·4
4th "	125·9	127·5	150·4	142·2	131·0	92·2
B Group (33 Cows)						
5th Lactation	100·0	100·0	100·0	100·0	100·0	100·0
6th "	100·6	106·7	110·4	109·5	104·5	104·8
7th "	99·2	100·5	111·5	105·7	94·3	89·1
C Group (26 Cows)						
7th Lactation	100·0	100·0	100·0	100·0	100·0	100·0
8th "	94·9	94·6	93·4	98·0	92·6	98·2

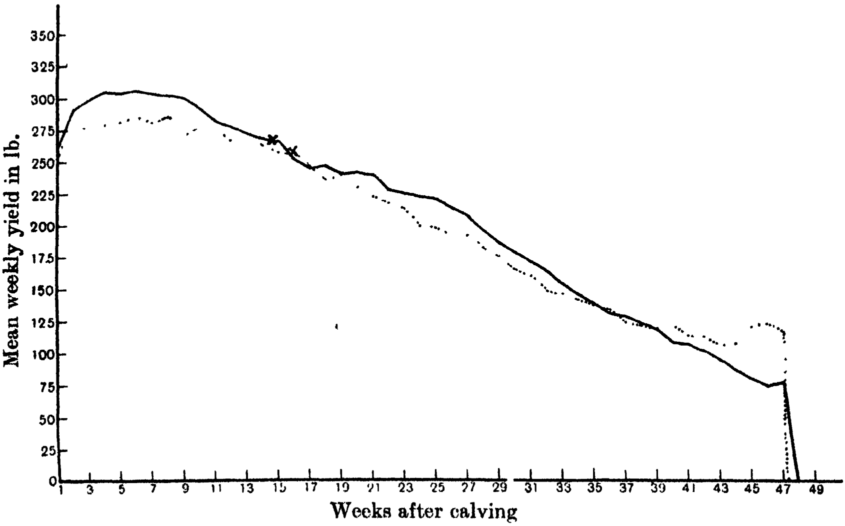


Fig. 35. Mean curves for lactations 7 and 8 of 26 cows (Mongrels).
7th lactation ——— 8th lactation • • • • Time of service ×

It seems, therefore, that these cows, though few in number, conform, on the average, very closely to the normal age variation, but it is obvious that we can only compare the lactations of the same group of cows with each other; this is the plan of Table XXVI.

In this the comparative yields of the three groups is shown for the Total Lactation, and for each ten-weeks period of it, the first column

the comparative yields indicated by the composite curve that has been built up to represent the age variation.

The figures for *A* Group run very smoothly, and the fact emerges that the increase from the 1st to the 4th lactation occurs entirely in the early part of the lactation; whilst the total yield increases by 27·5 per cent., that in the first 10 weeks increases by 50 per cent., that in the second period by 42 per cent., the third by 31 per cent., whilst there is actually a diminution of 8 per cent. in the fourth period, and the 2nd and 3rd lactations are intermediate. These lactation curves (as of course may be seen from Fig. 33) are then not parallel in any sense, the shape of the curve changing, at first rapidly and then slowly, from the long flat type for 1st calvers to the steep form for 4th calvers.

The difference from the 4th to the 5th lactation cannot be seen from these figures, but *B* Group takes up the tale again from there, and it is clear that the curves continue to become steeper up to the 7th lactation; in this group the 5th and 7th lactations give, as would be expected, approximately the same yields, but the rise to the peak for the 6th lactation is rather exaggerated compared to the normal; as before, the rise throughout occurs principally in the early part of the lactation, and is continued up to the 7th lactation despite the decrease in the total yield.

Up to this point we have a continuous picture of the variation; it seems to depend on two factors—as age increases the level at which the lactation commences rises, but the increase in total yield is not proportionate to this rise, as it is tempered by the "persistency factor" diminishing; the rise in the initial yield gradually slows down and from the 6th to the 7th lactation it is insufficient to compensate for the drop in persistency.

From this it might be expected that in the next stage a further rise (or no fall) would be found in the initial yield, and a still steeper form of curve; *C* Group however does not show this. The Month of Calving distributions are somewhat bunched (particularly for the 8th lactation), and consequently the results are not so regular, but it seems that the ordinates of the curves are nearly proportional throughout, the decrease being more in the 1st and 3rd periods and less in the 2nd and 4th, than in the total yield.

It is very difficult to see what the physiological processes can be that produce these effects; it is possible that the initial yield may be highly dependent on the area of the gland available for milk secretion, although the contrary has been held, without, however, any satisfactory

experimental evidence. If the area is largely responsible for the initial yield, it appears that it grows rapidly at first, then slowing down, but maintaining an increase at least as late as the 7th lactation.

No one knows why the yield falls as the lactation progresses, but it is certain that the rate of fall is influenced to a high degree by nutrition—if not merely the food which the cow eats or digests, at least the nutrition of the mammary gland; it is possible, therefore, that as the area of the gland increases, the nutrition possible becomes more inadequate, and a large flow cannot be maintained—*i.e.* the persistency is reduced; at the 8th lactation nutrition might be so deficient as to prevent the full expression of the area of the gland. Very conjecturally the view might be hazarded that milk secretion is largely governed by two limiting factors—the area of the gland in early life, and inadequate mammary nutrition later; in this connection see also what has been said above for High and Low Yielders (p. 60).

Corroboration of the fact that the Maximum Yield of which a cow is capable goes on increasing after she is past her prime, as indicated by total yield, is afforded by Gowen's (1) results in Advanced Registry Friesians; when working with 365-Day Yields he found that the prime was reached at $8\frac{5}{12}$ years of age, as opposed to $8\frac{1}{12}$ years when working with 7-Day (Maximum) Yields—a fairly small difference, but probably significant in view of the large numbers included.

To quote from a practical man, Van Wagenen (3) states—"It is perhaps not far wrong to say that a cow is no older than her teeth"; if this rather sweeping statement be accepted, even with reserve, a very simple explanation would be provided of how the inadequacy of nutrition, responsible for the decline in persistency arises.

As an alternative to this, the view may be advanced that the decline during the lactation may be due to senile changes in the gland itself—that is, that nutrition is affected by factors usually described as senility factors, senility being, in essence, a particular type of malnutrition associated with old age, or, in the case of the mammary gland, with progress of the lactation. Thus the cells of the mammary gland are rejuvenated at each pregnancy, and while each successive gestation may increase the size of the gland (owing to the foundation on which it starts, being that left by the previous pregnancy, and not that of the virgin state) the rate of senile decay during the progress of the lactation is greater with advance in age of the animal (as occurs in the other cells), until, ultimately, in the old animal (8th lactation) the power of rejuvenation is itself also partly lost. This does not preclude the fact that the

method of feeding (senility by malnutrition) or milking (senility by accumulation of waste products) may influence the shape of the curve.

Senility and nutrition seem to be, however, closely interrelated and much that has been ascribed to the latter may possibly be due to the former; this view has not been stressed in the present paper, but it should not be forgotten, as an alternative to some of the explanations that have been put forward.

It should, perhaps, be concluded that the above results are based on insufficient records to settle the question definitely, but a suggestion that in old age it was the persistency, rather than the capacity, which failed, emerged in studying the shape of the lactation curve in the Penrith data; it is hoped to go more deeply, at a later date, into what is a point at least of some scientific interest.

REFERENCES.

(1) GOWEN (1924). *Milk Secretion.* Baltimore.

(2) TURNER (1925). The Relation between Age, Weight, and Fat Production in Dairy Cows. *Mo. Exp. Sta. Bull.* 221.

(3) VAN WAGENEN (1922). *The Cow.* New York. P. 110.

(4) ZWAGERMAN (1925). De Oorzaken voor Variaties in de Melkopbrengsten. *Off. Org. van der Algemeen Nederlandschen Zuivelbond,* No. 1009.

Since the above was written the study of the changes in the shape of the lactation curve with age has been pushed further by Gaines ("Persistency of Lactation in Dairy Cows," *Ill. Agric. Exp. Sta. Bull.* 288, 1927).

(*Received October 8th,* 1927.)

THE RELATIVE PROPORTIONS OF EXCHANGEABLE BASES IN SOME SCOTTISH SOILS.

By A. M. SMITH.

(*Ministry of Agriculture Research Scholar, Edinburgh and East of Scotland College of Agriculture.*)

THE question of the absorbing complex of a soil and its content of exchangeable bases has received a considerable amount of attention in recent years, and several workers have emphasised the importance of the relative proportions of the exchangeable bases in determining the physical and chemical properties of the soil. The changes brought about by sea flooding have been dealt with by Hissink (6) and Page and Williams (13); the effects of manurial treatment by Gedroiz (4) and Page and Williams (12); the influence of fertilisers on soil reaction by Niklas and Vogel (10) and Tuorila (19) among others; the variation met with in normal soils by Kelley and Brown (7) and the writer (16); the absorbing complex as a basis of a genetic classification by Gedroiz (5).

A considerable amount of data is therefore available, but it seems that, apart from the investigations of Gedroiz (1), who employed solutions of various concentrations to measure the energy of absorption of different cations, little work has been done in the laboratory on the changes which may be produced in the relative proportions of exchangeable bases of a soil by neutral salts. The experiments to be described were designed to throw light principally upon the effect of the same manurial treatment on different soil types.

THE SOILS EXAMINED.

Nine soil types, which were sampled between September 1924 and March 1925, and have already been briefly described (*loc. cit.* p. 468), were employed in the investigation. Each soil examined was a composite sample of from six to twelve borings taken from the same group of layers at intervals over what appeared to be a uniform piece of ground. Fresh samples of soils 170 and 178, taken in September 1925, have been designated 170 N and 178 N respectively.

METHODS.

Two experiments were carried out with a solution containing equimolecular amounts of potassium chloride and sodium chloride and $N/50$

with respect to chlorine. Three soils were treated with $N/50$ potassium chloride, whilst seven soils were treated with $N/50$ calcium chloride.

In each experiment the soil and solution, in the ratio of 3 gm. to 10 c.c., were shaken at room temperature for about an hour and allowed to settle. The supernatant liquid was filtered and refiltered to get a perfectly clear solution. The soil was then washed until the presence of chlorine in the filtrate could not be detected, and allowed to dry at room temperature. The air-dried soil was then examined for exchangeable bases as previously described (*loc. cit.* p. 469). The results are given in Table I.

Table I. *The relative proportions of exchangeable bases in soils before and after contact with dilute solutions.*

No.	Solution used	Soil	Percentage loss at 105° C	Percentage loss on ignition	Exchangeable bases: Total Mg E*	Percentage of total: Ca	Mg	K	Na	pH
1.	$N/50$ (KCl + NaCl)	331	2·28	6·12	9·41	84·55	9·49	3·49	2·50	6·3
		331 T†	2·10	5·66	9·10	69·79	9·45	18·68	2·09	7·0
2.	$N/50$ (KCl + NaCl)	170 N	2·94	7·01	10·83	88·43	8·70	1·34	1·53	6·1
		170 N T	2·22	6·72	10·67	76·23	7·12	14·28	2·38	6·4
3.	$N/50$ KCl	170 N	2·14‡	6·72	11·62	89·13	8·09	1·29	1·46	6·3
		170 N T	2·31	6·20	12·18	71·19	5·69	20·82	2·33	6·2
4.	$N/50$ KCl	276	1·92	6·37	13·94	87·56	8·13	3·29	1·04	6·8
		276 T	1·92	5·86	14·44	72·43	8·64	17·22	1·72	6·8
5.	$N/50$ KCl	358	3·08	9·22	22·52	80·50	14·79	2·59	2·12	6·6
		358 T	3·24	8·84	20·43	69·36	12·90	14·42	3·32	6·7
6.	$N/50$ $CaCl_2$	170	3·67	6·65	11·29	85·33	9·67	2·24	2·77	6·3
		170 T	2·46	5·79	10·83	96·23	1·42	1·31	1·07	6·9
7.	$N/50$ $CaCl_2$	337	3·25	9·03	14·61	93·99	3·74	·73	1·48	6·9
		337 T	2·67	8·27	15·38	96·58	1·89	·81	·73	-
8.	$N/50$ $CaCl_2$	290	4·10	8·74	20·14	74·84	22·59	1·74	·84	5·8
		290 T	3·79	9·34	18·80	83·16	14·79	1·33	·72	—
9.	$N/50$ $CaCl_2$	277	1·81	4·35	8·92	85·07	8·29	3·70	2·92	7·0
		277 T	1·27	4·16	8·28	91·49	4·80	2·90	·81	6·8
10.	$N/50$ $CaCl_2$	331	—	—	10·56	86·12	8·55	3·12	2·33	6·3
		331 T	2·28	6·62	9·86	91·94	4·51	2·12	1·42	6·2
11.	$N/50$ $CaCl_2$	276	1·92	6·37	13·94	87·56	8·13	3·29	1·04	6·8
		276 T	1·92	5·99	14·21	88·24	8·03	2·28	1·41	6·5
12.	$N/50$ $CaCl_2$	358	3·08	9·22	22·52	80·50	14·79	2·59	2·12	6·6
		358 T	3·08	9·27	22·15	85·11	9·29	2·73	2·86	6·7

* Milligram equivalents per 100 gm. air-dried soil

† T denotes treated soil.

‡ About eighteen months elapsed between the analyses of 2 and 3 and a similar time between those of 1 and 10.

The $N/50$ solutions were analysed before and after contact with the soil and the results (Table II) have been calculated to express the milligram equivalents (Mg. E.) present in 1000/3 c.c., which was the volume of solution used for each 100 gm. soil.

Discussion of Results.

Changes in soil. The outstanding feature of the results is the great influence exerted by $N/50$ solutions. In *Exps.* 1 and 2 there has been a remarkable increase in exchangeable potassium chiefly at the expense of calcium. The sodium has scarcely been affected. That potassium has a greater energy of absorption than sodium has been revealed by the observations of many workers. Mention may be made of Lemberg's (9) experiments with leucite and analcite, methods devised for the estimation of "lime requirement" (3) and several investigations on base exchange (6, 8 and 14). A true indication of the energies of absorption of different cations can be obtained only by examining their absorption by a complex saturated with one other cation (4 and 20), and the present case is further complicated by the fact that a mixture of chlorides was used. However, the salts were present in equimolecular amounts and there has obviously been a selective absorption.

The alterations effected by the potassium chloride solution were even more pronounced; the amount of exchangeable potassium in soil 170 N was increased about seventeen times, whilst the percentage of exchangeable calcium was reduced from 89 to 71.

The changes brought about by the calcium chloride were not so pronounced as those effected by the alkali chlorides, and that was no doubt due to the fact that calcium was the predominating exchangeable base to begin with Generally speaking, the content of exchangeable calcium was increased at the expense of the other cations. For reasons already mentioned, it is not legitimate to compare the relative effects of calcium and potassium as replacing agents, but it would appear that, for the concentrations employed, magnesium is replaced more easily by calcium than by potassium (*cp. Exps.* 6, 11, 12 with 3, 4, 5).

The *p*H of the soil depends upon the entire composition of its absorbing complex and since there have been alterations in the proportions of exchangeable bases and in content of organic matter the final *p*H values may be the result of several factors. The effects obtained by concentrated solutions have been investigated by Spurway and Austin (17).

It was found that the absolute changes in the quantities of exchangeable bases did not always correspond to the changes in solution, because it was difficult to prevent the loss of a small quantity of fine mineral particles in the course of the treatments and the solution of organic matter was unavoidable. It is better, therefore, to compare the soils through the composition of their extracts.

Table II. *Composition of solutions before and after contact with soils.*

No.	Solution	Soil	Milligram equivalents per 1000/3 c.c. solution: Ca	Mg	K	Na	Total cations	Cl	Percentage of total: Ca	Mg	K	Na
1.	*N*/50 (KCl + NaCl)	—	—	trace	3·40	3·31	6·71	6·78	—	—	—	—
	Extract	331	1·97	·34	1·63	3·13	7·07	6·93	27·9	4·8	23·1	44·3
2.	*N*/50 (KCl + NaCl)	—	—	·05	3·38	3·32	6·75	6·79	—	—	—	—
	Extract	170 N	2·02	·39	1·42	3·14	6·97	6·87	29·0	5·6	20·4	45·0
3.	*N*/50 KCl	—	—	—	6·69	·03	6·72	—	—	—	—	—
	Extract	170 N	2·74	·42	3·64	·30	7·10	—	38·6	5·9	51·3	4·2
4.	Extract	276	2·33	·51	4·20	·36	7·40	—	31·5	6·9	56·8	4·9
5.	Extract	358	3·56	1·16	2·59	·39	7·70	—	46·2	15·1	33·6	5·1
6.	*N*/50 $CaCl_2$	—	6·50	·13	·02	·26	6·91	6·83	—	—	—	—
	Extract	170	6·04	·64	·08	·41	7·17	6·93	84·3	8·9	1·1	5·7
7.	*N*/50 $CaCl_2$	—	6·40	·10	·02	·24	6·76	6·75	—	—	—	—
	Extract	337	5·22	—	·05	·35	—	6·81	—	—	—	—
8.	Extract	290	4·83	1·65	·12	·42	7·02	6·86	68·8	23·5	1·7	6·0
9.	Extract	277	5·92	·49	·11	·37	6·89	6·81	85·9	7·1	1·6	5·4
10.	*N*/50 $CaCl_2$	—	6·69	—	·02	·03	6·74	—	—	—	—	—
	Extract	331	6·29	·65	·14	·34	7·42	—	84·7	8·8	1·9	4·6
11.	Extract	276	6·19	·81	·22	·34	7·56	—	81·8	10·7	2·9	4·5
12.	Extract	358	6·14	1·35	·18	·40	8·07	—	76·0	16·7	2·2	5·0
13.	Distilled water	—	—	—	—	—	—	—	—	—	—	—
	Extract	276	·28	·13	·06	·19	·66	—	42·4	19·7	9·1	28·8
14.	Extract	358	·53	·22	·06	·21	1·02	—	52·0	21·6	5·9	20·6

Changes in solution. It is generally agreed that there is equivalence of exchange unless secondary reactions take place. In the experiments under consideration secondary reactions could take place through the difference in acidity between soil and solution. The *p*H values of the solutions varied from 6·2 to 6·7, those of the soils (290 excepted) from 6·1 to 7·0. The concentration changes due to hydrogen were small, therefore, and masked by solubility effects. The concentration of the solution was invariably increased, but if allowance is made for the sodium which has come into solution it will be seen that there is a general proportionality between the composition of the solution and the relative proportions of the exchangeable bases. The percentage of calcium in solution, however, is always less than the percentage of exchangeable calcium in the soil, whilst the reverse usually holds for potassium. When the solution employed contains mixed alkali chlorides, then the percentage of magnesium in solution is less than that in the soil; when potassium chloride is used the magnesium in solution is about the same as that in the soil; when the solution employed is calcium chloride the magnesium in solution is always greater than that in the soil. It follows that, in the

presence of the other cations ($N/50$ solution), calcium is the most vigorous replacing agent and that the replacing power of magnesium is gradually reduced with increase in calcium concentration.

In six experiments the chlorine was determined volumetrically. The invariable "negative absorption" was probably due to the absorption of silver by soil particles sufficiently dispersed to pass through the filter. The change is so small, however, that there would seem to be justification for saying that the anion concentration remained unaltered.

Changes likely to occur in practice. It was realised that those quantities of salts were far in excess of what might be employed in the field. The ratio 10 : 3 for solution to soil corresponded to 30 in. of rainfall held up in the top 7–8 in. of soil (assuming that an acre of soil to that depth weighs about 2,000,000 lb.), but the ratio of salt to soil in the treatment with $N/50$ solution was ten times as great as a dressing of 10 cwt. of salts per acre. Two methods were adopted to arrive at some idea of the change which might be expected to take place in actual practice.

A. In view of the results obtained in absorption experiments by early workers, indicating a rough proportionality between the absorption and the quantity of soil employed, *Exps.* 1 *c* and 2 *c* (Table III) were carried out and the calculated results 1 *d* and 2 *d* have been added for reference. The soil examined in *Exp.* 1 *c* was obtained by mixing nine parts of the original soil 170 N with one part of the soil obtained by treating 170 N with the $N/50$ solution: similarly in case 2 *c*. The results 1 *d* and 2 *d* were calculated from 1 and 1 *a* and from 2 and 2 *a* respectively. It will be observed that there is a fairly close agreement between "*c*" and "*d*" in spite of the different equilibria which must have been set up and the increase in probable error involved in such a calculation.

Table III. *Variation in the relative proportions of exchangeable bases effected by treatment approaching manurial practice.*

			Exchangeable bases					
				Percentage of total				
No.	Treatment	Soil	Total Mg. E.	Ca	Mg	K	Na	*p*H
1.	—	170 N	10·83	88·43	8·70	1·34	1·53	6·10
1 *a*.	$N/50$ (KCl + NaCl)	170 N *a*	10·67	76·23	7·12	14·28	2·38	6·35
1 *b*.	$N/500$ (KCl + NaCl)	170 N *b*	10·73	88·84	7·41	3·23	·54	5·95
1 c.	—	(9/10 170 N + 1/10 170 N *a*)	11·32	85·65	8·47	2·92	2·94	6·23
1 *d*.	—	1 *c* calculated	10·81	87·21	8·55	2·64	1·61	—
2.	—	277	8·92	85·07	8·29	3·70	2·92	6·98
2 *a*	$N/50$ $CaCl_2$	277 *a*	8·28	91·49	4·80	2·90	·81	6·81
2 *b*.	$N/500$ $CaCl_2$	277 *b*	8·42	87·64	7·93	2·89	1·56	6·63
2 *c*.	—	(9/10 277 + 1/10 277 *a*)	8·87	85·39	7·85	3·60	3·17	6·94
2 *d*.	—	2 *c* calculated	8·86	85·71	7·94	3·62	2·71	—

B. In this case the solution was diluted ten times to give results 1 *b* and 2 *b*. The changes effected by the *N*/500 solutions were greater than those obtained by calculation for a tenfold increase in soil treated with *N*/50 solution. That was expected since, even with dilute solutions, the absorption in *Exp.* "*a*" would not be ten times as great as that in *Exp.* "*b*." The treatment in *Exp.* "*b*" was analogous to the effect of 1 cwt. of salts per acre and 3 in. rain on the top $\frac{3}{4}$ in. layer of soil or to 10 cwt., 30 in. and 7·5 in. respectively. Whether "*b*" gives a close approximation to what might occur in actual practice is open to question, but that the alterations found by both *A* and *B* are of the same order as those due to manurial treatment in the field is evident when comparison is made with the results obtained by Page and Williams (12).

The changes are small and it is quite likely that they are not greater than field error. Robinson and Lloyd (15) have dealt with the question of field error as arising in soil surveys, but it would be idle to suggest the magnitude of the error here until work has been done on the variation likely to be found for exchangeable bases in a soil type. Soils 170 and 178 were sampled in September 1924. They were sampled again twelve months later—170 N and 178 N. In the interval a crop of oats (no artificials added) had been taken from 170, and cattle and sheep had been grazed on 178 (grass after barley). The discrepancy in the results (Table IV) is more likely to be due to field error than to cropping, and is illustrative of the variation which is to be expected in any soil type.

Table IV. *Variation in content of exchangeable bases due to field sampling.*

		Exchangeable bases					
			Percentage of total				
Soil	When sampled	Total Mg. E.	Ca	Mg	K	Na	*p*H
170	September, 1924	11·29	85 33	9·67	2·24	2·77	6·33
170 N	„ 1925	10·83	88·43	8·70	1·34	1·53	6·10
178	„ 1924	9·01	85·55	8·81	1·65	4·01	6·35
178 N	„ 1925	7·40	92·06	4·06	1·85	2·03	6·41

In comparison the laboratory error is small (*loc. cit.* p. 470). Table V contains some results from soils 170 and 277. Samples of each of those soils, previously air dried and passed through a 3 mm. sieve, were divided into two fractions by means of a 1 mm. sieve. Each fraction was analysed by the usual method. In both soils there was more exchangeable calcium in the coarse fraction than in the fine fraction. The figures show that in those particular soils there is little or no gravel (1–3 mm.), or that the presence of gravel is counterbalanced by the relatively great amount of

exchangeable calcium in the binding material of the aggregates greater than 1 mm. diameter. The results are interesting as evidence in support of the views expressed by Bouyoucos (1) on the nature of the soil colloids.

Table V. *Exchangeable calcium in different soil fractions.*

Soil	Milligram equivalents per 100 gm. air-dried soil: Fraction: Under 1 mm.	Over 1 mm.	Average of two fractions	Ordinary sample
170	9·43	9·68	9·56	9·63
277	7·26	8·06	7·66	7·59

Conclusion.

No entirely satisfactory method of analysis has been developed to supply criteria of soil fertility and it is natural that considerable attention should have been directed to the availability of the absorbed bases (11). The general conclusion arrived at from different investigations is that the exchangeable cations are not available unless soluble salts are present. There will, of course, be slow secular changes due to weathering, and in those areas where the rainfall is great compared with evaporation, weathering really amounts to replacement of bases by hydrogen and gradual decomposition of the complexes. There will also be small changes due to variation in the concentration of the soil solution (2, 18). The data presented here would seem to show that ordinary manurial treatment with soluble salts is not likely to have such an effect upon the relative proportions of exchangeable bases as to produce rapid changes in the condition of the absorbing complex. The changes which might be effected in a few years would probably not be greater than the variation occurring in any soil. On the other hand, there are much bigger differences which are certainly fundamental soil differences. Those are due not only to the amount of absorbing complex but also to its nature, and the amount of the complex and its nature are characteristic of soil type.

Naturally, any chemical examination carried out in conjunction with soil classification should be confined to the more permanent properties of the soil, and it seems that information on the exchangeable cations would therefore be extremely valuable. Hence, although absorptive power and its relation to fertility may not be a convenient method of soil classification (as suggested by Way), it is extremely probable that soil types, as distinguished in the field by colour, texture, drainage, and other physical relationships, will be found to possess characteristic absorptive properties.

SUMMARY.

1. The relative proportions of exchangeable bases in nine soils from the east of Scotland area and the changes effected by dilute chloride solutions have been examined.

2. The changes due to $N/50$ solutions are large, and magnesium is displaced to a greater extent by calcium than by potassium.

3. The changes due to $N/500$ solutions are very small, comparable to what might be expected in manurial practice, and not greater than field sampling error.

4. The content of exchangeable bases and their relative proportions, therefore, seem to be fairly permanent for any soil under normal conditions, but vary considerably from soil to soil, and should prove useful as an additional characteristic of soil type as distinguished in the field.

I should like to acknowledge my indebtedness to Dr W. G. Ogg for the interest he has taken in the investigation and for placing at my disposal most of the soil samples examined.

REFERENCES.

(1) BOUYOUCOS, G. J. (1926). *Soil Sci.* **21**, 481.
(2) BURD, J. S. and MARTIN, J. C. (1924). *Soil Sci.* **18**, 151.
(3) DAIKUHARA, G. (1914). *Bull. Imp. Cent. Agric. Expt. Stat., Japan*, **2**, 1.
(4) GEDROIZ, K. K. (1916). *Zhur. Opit. Agron.* **17**, 472.
—— (1919). *Zhur. Opit. Agron.* **20**, 31.
(5) —— (1925). *Nossov. Agric. Expt. Stat., Paper No.* 38, Leningrad.
(6) HISSINK, D. J. (1922). *Intern. Mitt. Bodenkunde*, **12**, 81.
(7) KELLEY, W. P. and BROWN, S. M. (1924). *California Agric. Expt. Stat., Tech. Paper* 15.
(8) KELLEY, W. P. and CUMMINS, A. B. (1921). *Soil Sci.* **11**, 139.
(9) LEMBERG, J. (1876). *Z. Deut. geol. Ges.* **28**, 519.
(10) NIKLAS, H. and VOGEL, F. (1925). *Z. Pflanz. Düng.* B, **4**, 375.
(11) VON NOSTITZ, A. (1924). *Landw. Versuchs. Stat.* **103**, 159.
(12) PAGE, H. J. and WILLIAMS, W. (1925). *Trans. Faraday Soc.* **20**, Part 3.
(13) —— —— (1926). *Journ. Agric. Sci.* **16**, 551.
(14) RAMANN, E. (1924). *Soil Sci.* **18**, 387.
(15) ROBINSON, G. W. and LLOYD, W. E. (1915). *Journ. Agric. Sci.* **7**, 144.
(16) SMITH, A. M. (1925). *Journ. Agric. Sci.* **15**, 466.
(17) SPURWAY, C. H. and AUSTIN, R. H. (1926). *Soil Sci.* **21**, 71.
(18) STEWART, G. R. (1918). *Journ. Agric. Res.* **12**, 311.
(19) TUORILA, P. (1926). *Journ. Peat Cultivation Soc.* (Finland), **30**, 95.
(20) WIEGNER, G. (1925). *Zsigmondy Festschrift*, p. 341.

(*Received June* 19*th*, 1927.)

OBSERVATIONS ON *B. RADICICOLA*, BEIJK.

By T. GIBSON.

(*Bacteriology Department, The Edinburgh and East of Scotland College of Agriculture.*)

(With Plates I and II.)

Introduction.

The nitrogen fixing organisms which inhabit the root nodules of leguminous plants have attracted considerable attention since their existence was first suspected. Investigations have been made of the conditions suitable for the growth of these bacteria and of methods of inoculating soils with pure cultures in order that their economic value as fixers of free nitrogen may be utilised to the greatest possible extent. Much interest has also been aroused by the growth forms and the methods of reproduction of the nodule bacteria, partly on account of their purely scientific significance, and partly because greater knowledge of the behaviour of these organisms may lead to more effective methods of utilising them for agricultural purposes.

Before bacteriological methods had been developed the earlier investigators centred their attention on the root nodule. The peculiar types of growth produced by the organism in the nodule led most of these workers to the erroneous conclusions that it belonged to the fungi or myxomycetes. With the isolation of *B. radicicola* by Beijerinck (1) in 1888 and almost immediately afterwards by Prazmowski (16) the study of the organism was put on a satisfactory basis. These authors described several of the growth forms. The next important advance in the elucidation of the life history of the organism was made by Löhnis and Smith (13) who recognised that a number of the growth forms, several of which had been described previously, were produced in the same way as those of other bacteria, thus providing a clue to their physiological significance. This paper deals with a further investigation of the morphology and reproductive processes of the nodule bacteria.

Methods.

Only the European or peritrichic group of leguminous nodule bacteria will be discussed here. Most of the strains examined were stock cultures of the Nodule Laboratory of the United States Department of Agriculture,

and were kindly supplied by Mr L. T. Leonard. They had been isolated from the following plants:

Trifolium repens,	*Melilotus alba*,
Trifolium pratense,	*Pisum sativum*,
Trifolium hybridum,	*Vicia sativa*,
Medicago sativa,	*Phaseolus vulgaris*.

Each strain after having been tested for purity by planting was cultivated on various media, some being favourable and others unfavourable to growth. Bacteria tend to behave differently under different environmental conditions, and by growing them on a wide range of media opportunity is given for the study of their different growth forms. The media employed were bouillon, beef agar, beef gelatine, mannite soil extract, mannite soil extract agar, potato, milk, sterile soil moistened with 0·05 per cent. mannite solution, potato agar (made from potato extract with the addition of 0·05 per cent. KH_2PO_4 and 0·1 per cent. KNO_3, the extract being prepared by boiling 500 gm. potato in 1600 c.c. water), mannite nitrate solution and mannite nitrate agar. The last two were made according to Löhnis and Smith (13). The reaction of these media was generally adjusted to approximately pH 7. In addition, several of the strains were tested on various other media, but little further information concerning the behaviour of the organisms was secured thereby.

For routine purposes films were fixed by heat and stained with aqueous fuchsin. When delicate structures were being examined Dobell's (5) drop method of fixation with formalin and alcohol was employed. For special purposes other methods of staining and Indian ink and Congo red films were used. All these methods have advantages but none is perfectly reliable. It cannot be too strongly emphasised that whenever a doubtful or unusual structure is encountered on a stained preparation of bacteria the most trustworthy method of arriving at its true nature is to examine the living material in a hanging drop. Hanging drops were therefore examined when stained preparations indicated that this was desirable. The development of cultures on the different media was followed closely by microscopic examinations, the intervals between successive tests being sufficiently short to show how changes were taking place. When distinctive cell forms appeared they were transferred to fresh substrates on which their development was then followed. This method of tracing development by means of periodic examinations is of course not infallible, but if its limitations are kept in mind it may yield

correct results more easily than the difficult and tedious process of observing directly the development of an individual organism.

Morphology.

Rods. The cell generally regarded as the typical form of *B. radicicola* is the small, motile (peritrichic) rod of variable length shown in Pl. I, Fig. 1. This form generally predominates in young cultures in mannite soil extract and mannite mineral solution or on agars made from these. Young cells in mannite soil extract are generally uniformly stainable but on the other media just mentioned only granules or segments of the rods take the stain as a rule. On media containing mannite and various sugars the small rods usually produce a large amount of mucilaginous material which is readily stainable. On account of its abundance colonies on a suitable agar have a characteristic slimy appearance and flow readily when held in a sloping position. It may also cause liquid cultures to become very viscid in consistency. As the age of a culture increases the small rods generally enlarge and become more ovoid or spindle-shaped and sometimes curved. On mannite media, particularly on mannite agar, the cells soon become unstainable or show only a faint alveolar appearance. This is not necessarily a sign of death as such cells may multiply when transferred to a fresh medium.

Cultures of *B. radicicola* may be found in which the cells on mannite agar are very unlike the usual rod-shaped bacteria even during the first hours of growth on a fresh medium. In such cultures the cells, which are frequently irregularly spherical, ovoid or wedge-shaped, may be completely unstainable or may only show a faintly stainable granule; or faintly stained or granular rod-shaped structures may be contained within unstainable capsules. At times nothing stainable within the capsules can be recognised. These capsules are quite distinct from the usual slime in which the rods are always embedded for the slime takes the stain with avidity. Thread-like growths consisting of a series of faintly stainable granules enclosed in capsular material are common in cultures of this type. Similar cultures of *B. pneumoniae* have been recorded by Toenniessen (19, 20) who regarded the phenomenon as a case of mutation.

Coccoids. Cultures on beef and potato agar and on potato frequently consist in large part of coccoid and ovoid cells. This was found more particularly when the growth was unusually luxuriant. Several cultures were obtained on the media just mentioned in which the great majority of the cells were strictly spherical. They tended to be somewhat variable in size. Some of the potato cultures in which these forms became pre-

dominant produced a jet black growth, a cultural feature which does not appear to have been recorded previously. The coccoid cells apparently originate either from the gonidia or from regenerative bodies formed as buds. These will be referred to later. Photographs showing coccoids are reproduced as Pl. I, Figs. 2 and 3.

Branched Forms. B. radicicola is probably the best known example of an organism belonging to the so-called true bacteria which frequently produces branched forms. T- and Y-shaped bodies are the characteristic form of the organism in the root nodules of *Vicia*, *Pisum* and other plants. This branching is of the "true" type. It is brought about by an elongation of one or more buds produced laterally on a rod and may proceed to the formation of secondary branches. The Y-shaped forms arise by a sympodial type of branching. By examining cultures exhibiting all stages of branching it may be seen that the initial bud and later the tip of the branch frequently contains one of the deeply staining granules which are common in cells undergoing this process. Buchanan (3) and others have recorded the same fact. Löhnis (11) is of the opinion that the granules are nuclei which control this as well as other types of development.

Branched forms generally result from the development of small rods. Those shown in Pl. I, Fig. 4 had originated in this way. More rarely they are produced when large spherical cells germinate and produce more than one germ-tube. A third and still rarer type of branched body is represented by so-called sclerotia, a photograph of which is reproduced as Pl. II, Fig. 18.

Gonidangia. The term gonidangium has been proposed by Löhnis (11) for a large cell containing a number of granules which on liberation from the mother cell function as gonidia. Large spherical, pear-shaped, spindle-shaped and branched bodies, which are apparently capable of acting as gonidangia, were obtained frequently on potato and on beef and potato agars. In cultures on other media they were as a rule only present in small numbers. The types found most frequently are illustrated in Pl. I, Figs. 5 to 9. The spherical forms usually contain very minute, deeply staining granules which may be seen within the largest body in Pl. I, Fig. 8. Although the granules were very clearly defined under the microscope they have been largely obliterated in the photographs. The large spherical body in Pl. I, Fig. 9 is not clearly defined in outline because, owing to its thickness, a sharp optical section lay on a different plane from the budding form below for which the photograph was primarily taken. In most cases at least the spherical gonidangia are produced by the enlargement of small coccoid cells. Intermediate types are shown in Pl. I, Fig. 8. Gonidangia

of other shapes generally contain much larger granules, unstainable with aqueous fuchsin, and are probably always derived from rod-shaped cells. These latter types of gonidangia were frequently referred to in the earlier literature as *Bläschenbakteroiden* and their nature has been the subject of several investigations. The bodies in the gonidangia which do not stain readily are not vacuoles for they may be differentially stained by the usual spore-staining methods and some are sufficiently acid-fast to be stained by the Ziehl-Neelsen method. Further, they become at least partially stainable after treatment with various organic solvents, such as acetone and chloroform, which shows that they are not entirely composed of fatty and waxy materials. The unstainable granules have not appeared clearly on the photographs principally because the preparations had to be washed with xylol and restained for photographing. In Pl. II, Fig. 14 however, which shows the gonidangia in a state of dissolution, the unstained globules can be recognised.

Ordinarily the gonidangia would be classed as involution forms. There are several reasons for not adopting this view. They are the characteristic form of the organism in its natural habitat, the root nodule. Nobbe and Hiltner (15) found that the time when nitrogen fixation begins in the plant coincides with the formation of these so-called bacteroids. That a stage in the life history of the organism which is associated with marked physiological activity should be regarded in any way as degenerate appears unreasonable. In addition to the liberation of viable gonidia a further development of the gonidangia themselves may occur. In the case of Azotobacter the large cells which may act as gonidangia multiply as such by the usual process of fission. In this investigation the gonidangia of *B. radicicola* were never found to reproduce cells other than gonidia except by budding or by a germination process which gave rise to the usual rod-shaped form. More frequently, however, the gonidangia, after they had grown to full size, disintegrated and liberated their contents without showing any other modes of development.

Gonidia and Dwarfed Growth. Most of the earlier workers who studied the nodule bacteria apparently recognised gonidia and called them "swarmers" (*Schwärmer*) or "zoospores." Beijerinck (1) found that these, like the motile gonidia of other bacteria, possessed a single polar flagellum, a fact which distinguishes them from the full-grown peritrichic rods. Gangulee (6) records having stained the gonidial flagellum before the gonidium itself became free from its mother rod. Löhnis and Hansen (12) made similar observations.

In this work the gonidia of *B. radicicola* were frequently observed.

Those produced by rods vary in size from minute particles on the limit of microscopic visibility to coccoid and ovoid cells of nearly the same width as the rod-shaped forms which produced them. As far as could be ascertained by hanging drop preparations, active motility is a general characteristic of at least the smaller gonidia whether they be produced from rods or from gonidangia. Gonidia exhibit a darting movement which is distinct from the slower and more regular motion of the rods.

The spherical unstainable bodies produced in the large pear-shaped gonidangia are probably to be regarded as gonidia. They frequently grow to much larger size before liberation than the small stainable gonidia just mentioned. Motility was never observed in these large gonidia loaded with fatty or waxy materials which render them highly refractile.

Löhnis and Smith (11) introduced the term dwarfed growth for the minute, usually oviod cells which are produced when gonidia multiply by fission. Dwarfed growths of *B. radicicola* were sometimes found in cultures on potato agar and more rarely on other media. In such cases the small cells usually occurred in clumps scattered through the other elements of the culture as in Pl. I, Fig. 10.

Microcysts. Löhnis (11) designated cells which developed a thick wall and thus took on the character of resting bodies as microcysts. Cells which appear to be microcysts were common in cultures on mannite agar but were also seen in mannite soil extract. A clump of these cells is shown in Pl. I, Fig. 11 with some of the usual unstained rods scattered round it. At first sight the microcysts might be taken for spores as only the thick cell wall takes the stain, but their heat resistance is not markedly different from that of the vegetative cells. They always occurred in characteristic clumps as in Pl. I, Fig. 11. The reason why such forms are classed as microcysts is that their further development consists of a germination similar in every way to that of spores.

REPRODUCTIVE PROCESSES.

Fission. Rods, ovoid, coccoid and dwarfed cells may multiply by the usual process of binary fission, but spherical and pear-shaped gonidangia were not observed to reproduce in this manner. Branched forms may multiply by breaking up into straight rods, a process which was followed directly under the microscope by Prazmowski (16) and Dawson (4).

Budding. The formation of buds which subsequently enlarge to full sized cells is a process which is often supposed to be peculiar to yeasts and certain other fungi in which either the conidia or mycelium may undergo budding. However, a number of investigators have described this mode

of reproduction among bacteria and several have followed the growth of the buds to new cells (Löhnis (11)). In the case of *B. radicicola* budding has been seen by several workers and it led Greig-Smith (7) and Schneider (17) to conclude that the organism should be classified with the yeasts while Buchanan (3) suggests placing it in a group by itself which showed relationships to both yeasts and bacteria.

Budding cells have frequently been observed during this investigation and are illustrated in Pl. I, Figs. 2, 3, 9 and 12. When the large spherical cells to be seen in Pl. I, Figs. 8 and 9 multiply by budding they show considerable similarity to yeasts. Large budding forms have, however, been observed in cultures of other bacteria. The nodule organisms do not occupy an isolated systematic position on account of this method of reproduction. It has, for example, been pointed out by Löhnis (10) that when general morphological and cultural characteristics are considered there is a complete series of intergrading forms between *B. radicicola* and the Coli-aerogenes group.

Almost any type of cell may multiply by budding. A rod producing a lateral bud is shown in Pl. I, Fig. 2, while coccoid and ovoid cells forming buds may be seen in Pl. I, Fig. 3. The culture from which these two photographs were made—one exhibiting an exceptionally luxuriant growth—showed no other method of multiplication than budding. No indications of binary fission could be detected. Many of the buds, and especially the smaller ones, do not appear clearly on the photographs. Multiplication by budding is particularly common among coccoid cells. Pl. I, Figs. 8 and 9 are photographs of a culture in mannite soil extract which possessed an initial reaction of pH 5. During the eleven weeks in which this culture was kept under observation direct fission was in abeyance while multiplication by budding was always taking place. In certain cultures, as for example the one which produced the unstained cells illustrated in Pl. I, Fig. 12, it is impossible to draw a sharp distinction between fission and budding. The two processes merge into each other. It might be pointed out in this connection that among the yeasts there are certain types which show a method of reproduction intermediate between typical budding and typical fission (Guilliermond (8)). There is no fundamental distinction between the two processes.

It may be thought that some of the appearances recorded may have been brought about by two organisms of different origin adhering to each other by chance. That this is not the correct explanation is shown by the facts that large numbers of budding forms occur in certain cultures and that all gradations between the smallest buds and fully developed

regenerative bodies or vegetative cells may be seen attached to the parent organisms, both in stained and in hanging drop preparations.

Liberation of Gonidia. A considerable number of investigators have observed the liberation of minute, usually motile granules from bacterial cells (Löhnis (11)). Several have followed up the development of these granules, or gonidia, to cells of the usual size. The small dimensions of this reproductive organ and the difficulties of observation largely account for its lack of general recognition.

The rods of *B. radicicola* have a great tendency to form deeply stainable granules, most frequently one or two being produced in each cell. These granules which may function as gonidia can apparently escape either from the ends or sides of the rods. The process can be considered as the first stage of budding, the minute bud becoming free immediately on formation instead of developing to a larger regenerative body or branch. The liberation of gonidia by nodule bacteria has been studied previously by Greig-Smith (7), Bewley and Hutchinson (2), Gangulee (6), and others; and Thornton and Gangulee (18) have investigated methods of stimulating this process of reproduction in soil.

The gonidangia—the highly inflated cells which produce a large number of gonidia—as a rule appear to break down completely and liberate all their contents simultaneously.

On liberation the gonidia may develop to cells of larger size, either to coccoid regenerative bodies or to rods, or they may first multiply for a period by fission, thus producing the dwarfed growth already referred to.

With regard to the small and intensely stainable type of gonidium the evidence for its reproductive function is as follows: it is usually found to be highly motile, thus proving that it is not a mere lifeless particle. Further, in cultures in which gonidia are being produced, cells with all gradations in size between these minute granules and rods of normal dimensions are to be found. The smallest gonidia are smaller in diameter than the rods which excludes the possibility of their being formed by rods breaking up into short segments.

No observations have been made on the development of the larger, unstainable type of gonidia. They are apparently of a similar nature to certain of the gonidia of Azotobacter described by Löhnis and Smith (14).

Formation of Regenerative Bodies. A clear-cut distinction cannot be made between gonidia and regenerative bodies as defined by Löhnis (11). If a gonidium begins to develop while still within or attached to a parent cell it becomes a regenerative body. The large buds produced by coccoid

cells and gonidangia which were described above are one type of regenerative body produced by *B. radicicola*. The formation of terminal swellings on rods by the growth of regenerative bodies was observed and is illustrated in Pl. I, Fig. 2, and also in Pl. I, Fig. 6 where further growth has resulted in the formation of large gonidangia. Regenerative bodies usually stain well but the formation of unstainable terminal bodies is very common in cultures of the nodule bacteria on various media. It has been claimed that if the tendency to form terminal regenerative bodies can be stabilised the bodies in question may acquire the character of spores and a sporulating strain may be developed from a previously non-sporing organism. Attempts were made by heating cultures producing terminal regenerative bodies to bring about such transformations but they were unsuccessful. These negative results of course do not disprove the claims that such alterations are possible.

The further development of coccoid regenerative bodies usually consists of an elongation to the rod form, but in cultures where multiplication by fission had been largely or entirely superseded by budding the regenerative bodies merely developed to larger coccoid cells which again reproduced by budding. Regenerative bodies elongating to rods can be seen in Pl. I, Fig. 3.

Germination. Under this designation are included the cases where a rod or a filamentous form grows out from a body of another character. The cells which have been called microcysts apparently always develop in this way. When they are transferred to a fresh medium and microscopic examinations are made at intervals they are found to enlarge and become easily stainable and each produces a faintly staining rod, sometimes through an obvious split in the cyst wall. The process is similar in every respect to the germination of a spore. Germinating microcysts are shown in Pl. II, Fig. 13. Gonidangia may also undergo a process of germination, sometimes producing more than one germ-tube. This apparently results from a particular type of development of the contained gonidia or nuclei.

Symplasm and Regeneration.

Löhnis and Smith (13) proposed the term symplasm for the amorphous product formed by the dissolution of bacterial cells. They stated that from this material cells of various types may be reproduced, that all bacteria periodically enter the symplastic stage as an essential part of their life cycle and that all types of bacterial cells and reproductive organs may form symplasm. Emphasis was laid on the fact that the

symplasm was the connecting link between the different types of growth of Azotobacter.

In this investigation all the appearances described and illustrated by Löhnis and Smith in this connection were observed in cultures of *B. radicicola*. Cells undergoing dissolution in clumps were easily recognised. Figs. 14 and 15 illustrate the process in the case of the large gonidangia which are especially liable to disintegrate in this way. When the material produced was easily stainable it was either amorphous or possessed a fluffy appearance: when it refused to take the stain or only became coloured faintly it was of the amorphous type. Everyone will admit that such material may arise in bacterial cultures as a result or disintegration or autolysis of the cells, but the claim that a regeneration of new cells may take place from the dissolved mass is still frequently looked upon with doubt. However, if the development of cultures is closely followed microscopically this regeneration does appear to take place. It must be admitted that in the case of *B. radicicola* evidence for regeneration has to be derived solely from microscopic examination of cultures in which various cell types are generally present. The phenomenon does not lend itself to quantitative or clear-cut experimental proof.

Pl. II, Fig. 16 is a photograph illustrating the growth of intensely stainable granules or regenerative units to coccoid bodies which also take the stain deeply. Such pictures were not seen frequently. Pl. II, Fig. 17 shows a common appearance in cultures on mannite agar. In the centre of the clump are large ovoid bodies which are apparently developing into the usual small rods seen at the margin. Another type of regeneration of rods which was frequently encountered consisted of the appearance of stainable granules, each contained in an entirely unstainable ovoid or spherical capsule. Sometimes the capsules contained nothing stainable. On multiplication by fission these forms appeared to reproduce the ordinary granular rods. This phenomenon was especially noticeable in cultures which were being transferred every twenty-four hours on mannite agar over a considerable period. The large and very irregular branching bodies shown in Pl. I, Fig. 18 are similar to a type of growth from symplasm to which Löhnis gave the name sclerotia. These were rarely encountered in *B. radicicola* cultures.

The large deeply stained bodies illustrated in Pl. II, Fig. 19 and also, but less distinctly, at the left side of Pl. I, Fig. 10, appear to be encapsulated pieces of symplasm such as have been described in cultures of other bacteria (11). In hanging drops they have a homogeneous appearance and a clearly defined exterior. These bodies are apparently similar to the

macroplasts described by Lankester (9). The relatively enormous, lobed and nodulose structure in Pl. II, Fig. 20 is perhaps of a similar nature. The milk culture in which this material appeared was showing the usual peptonisation. In hanging drop preparations and wet mounts grape-like masses of solid material were found, the individual lobes or swellings of which varied in size from those photographed and shown in Pl. II, Fig. 20, which were the largest encountered, to small bodies no larger than the common cocci. These peculiar structures were not visibly altered by treatment with xylol, saturated NaCl solution or with acids, including concentrated mineral acids. They disappeared when treated with $N/1$ NaOH. No organisms other than *B. radicicola* developed when transfers were made to a variety of other media. While nothing definite can be claimed concerning the nature of those bodies they may be compared with the so-called infection thread in the nodule.

Interpretation of Bacterial Morphology.

An explanation which is likely to be offered for many of the observations recorded in this paper is that "involution forms" have been dealt with. It is one of the current conceptions of bacteriology that all bacterial forms differing in size, shape and stainability from what is considered to be typical for the particular organism are dying or degenerate involution forms. The accumulation of products of metabolism is usually held to be responsible for such changes because of the fact that most of the better known bacteria when grown on the media generally employed for microscopic examination exhibit a uniform morphology in young cultures while the variations mentioned above occur in older cultures. This appears to be the only evidence for the belief that the so-called involution forms are connected with death of the organisms, an occurrence which certainly takes place as the age of a culture increases.

As a result of the observations on which this paper is based it may be stated that when *B. radicicola* is grown on a considerable variety of media and is transferred from one medium to another when the cultures are at different stages of development, such characteristics of the cells as shape, size, and stainability show no relation to the age of the culture or to the amount of macroscopic growth produced. Cultures in an early stage of development when growth is just becoming visible and cultures producing a luxuriant growth sometimes exhibit the greatest variability in cell form. On the other hand, when the organisms were placed under unfavourable conditions, as for example in media adjusted to an unsuitable reaction or in media containing 3 per cent. NaCl, they grew as

uniform small rods only. Unstainable cells were also observed to multiply. When they produced buds the latter frequently became stainable. The state of the culture used as the inoculum and many other factors of which the composition of the medium is one of outstanding influence determine the type of development. It is generally acknowledged that environmental factors have frequently a marked effect on bacterial morphology. Whether the changes produced are pathological or represent a normal course of development which the organism under certain circumstances may follow can only be determined by observing the fate of the different forms. If they exhibit a reproductive process the pathological explanation is improbable; if the same process may be seen to occur with different bacteria and with the same organism under different circumstances it becomes practically certain that a normal process is being observed. A number of forms of the nodule bacteria to which the term "involution" would generally be applied are illustrated on the photographs accompanying this paper. Their development was in most cases traced microscopically and was found to follow the same lines as have been recorded for other bacteria. The view is therefore again put forward that so-called involution forms of the bacteria represent normal stages in their development.

Most of the work on which this paper is based was carried out in 1925 at the Bureau of Plant Industry of the United States Department of Agriculture. I am greatly indebted to Prof. F. Löhnis for much help in carrying out the investigation, and I also wish to thank Mr F. L. Goll for taking the photographs.

SUMMARY.

1. Cultures of *B. radicicola* derived from eight different host plants have been studied and a description is given of the morphology and reproductive processes of the organisms.

2. The growth forms described include rods, coccoids, branched forms, gonidangia, gonidia and dwarfed growth, and microcysts.

3. The different cell types represent normal stages in the development of the organisms.

4. The reproductive processes described are fission, budding, liberation of gonidia, formation of regenerative bodies, and germination.

5. The formation of symplasm and the regeneration of cells is discussed.

EXPLANATION OF PLATES.

Magnification × 1000 in every case.

Preparations stained with aqueous fuchsin.

PLATE I.

Fig. 1. *Pisum sativum* strain. Mannite soil extract agar. One day. Small rods.

Fig. 2. *Melilotus alba* strain. Potato. Two days. Rods and coccoids. (*a*) Rods forming buds. (*b*) Rods with terminal regenerative bodies.

Fig. 3. *Melilotus alba* strain. Potato. Two days. Coccoids elongating and budding.

Fig. 4. *Trifolium repens* strain. Beef agar. One day. Branched forms.

Fig. 5. *Vicia sativa* strain. Potato. Ten days. Rods developing to gonidangia.

Fig. 6. *Vicia sativa* strain. Potato. Five days. Rods developing to gonidangia.

Fig. 7. *Vicia sativa* strain. Potato. Five days. Large gonidangia.

Fig. 8. *Trifolium hybridum* strain. Mannite soil extract, *p*H 5. Five weeks. Coccoids developing to spherical gonidangia.

Fig. 9. *Trifolium hybridum* strain. Mannite soil extract, *p*H 5. Five weeks. Spherical gonidangia; budding.

Fig. 10. *Vicia sativa* strain. Potato agar. Four days Dwarfed growth; also encapsulated symplasm.

Fig. 11. *Trifolium hybridum* strain. Mannite soil extract agar. Fourteen days. Clump of microcysts; also unstained rods.

Fig. 12. *Phaseolus vulgaris* strain. Mannite nitrate agar. Fifteen days. Unstainable cells budding.

PLATE II.

Fig. 13. *Phaseolus vulgaris* strain. Beef agar. One day. Germination of microcysts.

Fig. 14. *Vicia sativa* strain. Potato. Five days. Dissolution of gonidangia.

Fig. 15. *Pisum sativum* strain. Beef agar. Four days. Dissolution of gonidangia.

Fig. 16. *Trifolium hybridum* strain. Mannite soil extract. Five weeks. Development of regenerative units.

Fig. 17. *Trifolium repens* strain. Mannite soil extract. Two days. Regeneration of rods.

Fig. 18. *Vicia sativa* strain. Beef agar. Thirteen days. Sclerotia.

Fig. 19. *Vicia sativa* strain. Potato agar. Six days. Encapsulated symplasm.

Fig. 20. *Melilotus alba* strain. Milk. Six weeks.

REFERENCES.

(1) Beijerinck, M. W. (1888). *Bot. Ztg.* **46**, 725–735, 741–750, 757–771, 781–790, 797–804.

(2) Bewley, W. F. and Hutchinson, H. B. (1920). *Journ. Agric. Sci.* **10**, 144–161.

(3) Buchanan, R. E. (1909). *Centrbl. f. Bakt. II Abt.* **23**, 59–91.

(4) Dawson, M. (1900). *Proceed. Roy. Soc. London*, **66**, 63–65.

(5) Dobell, C. C. (1911). *Quart. Journ. Microsc. Sci.* **56**, 395–506.

(6) Gangulee, N. (1926). *Ann. App. Biol.* **13**, 360–373.

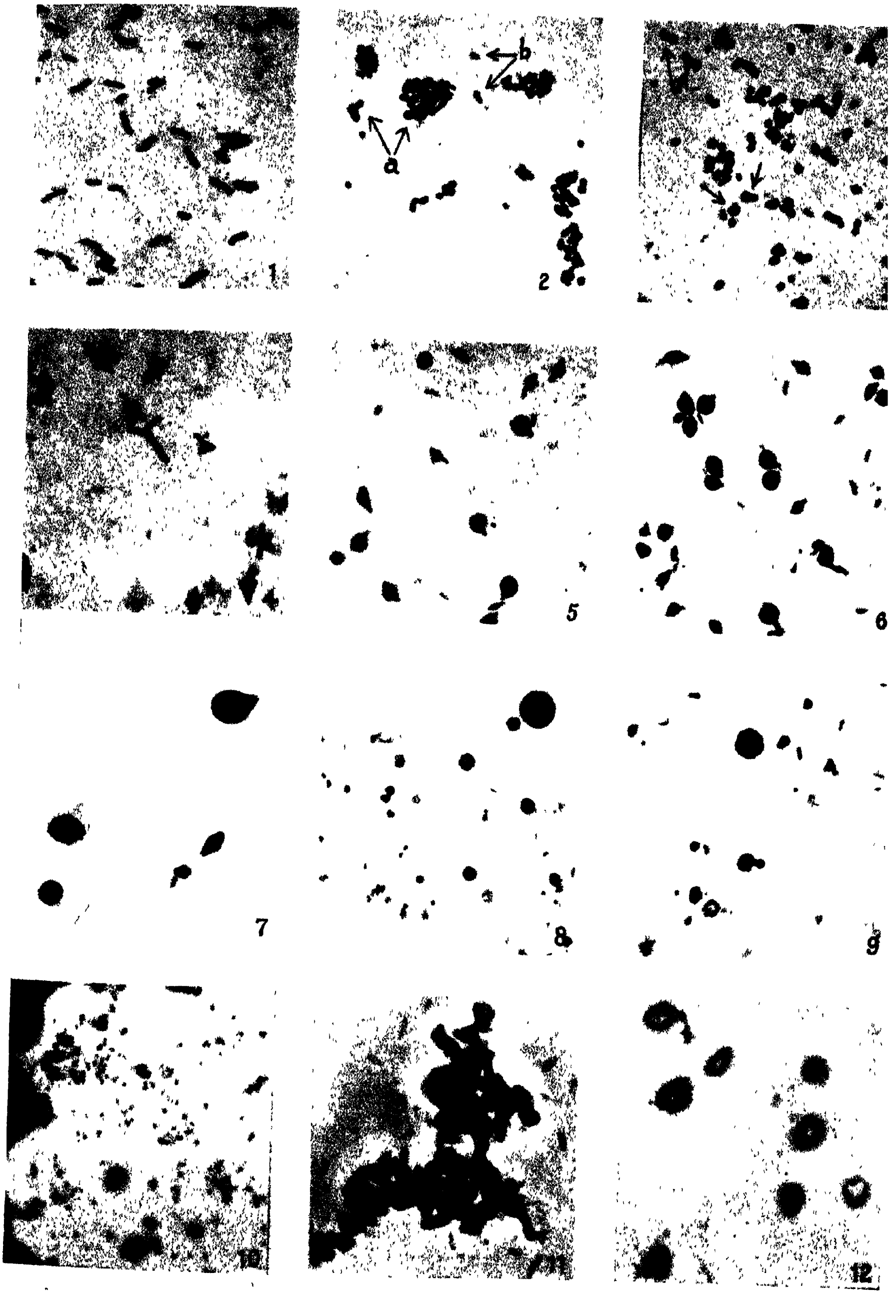
(7) Greig-Smith, R. (1900). *Proceed. Linn. Soc. N.S. Wales*, **24**, 653–673.

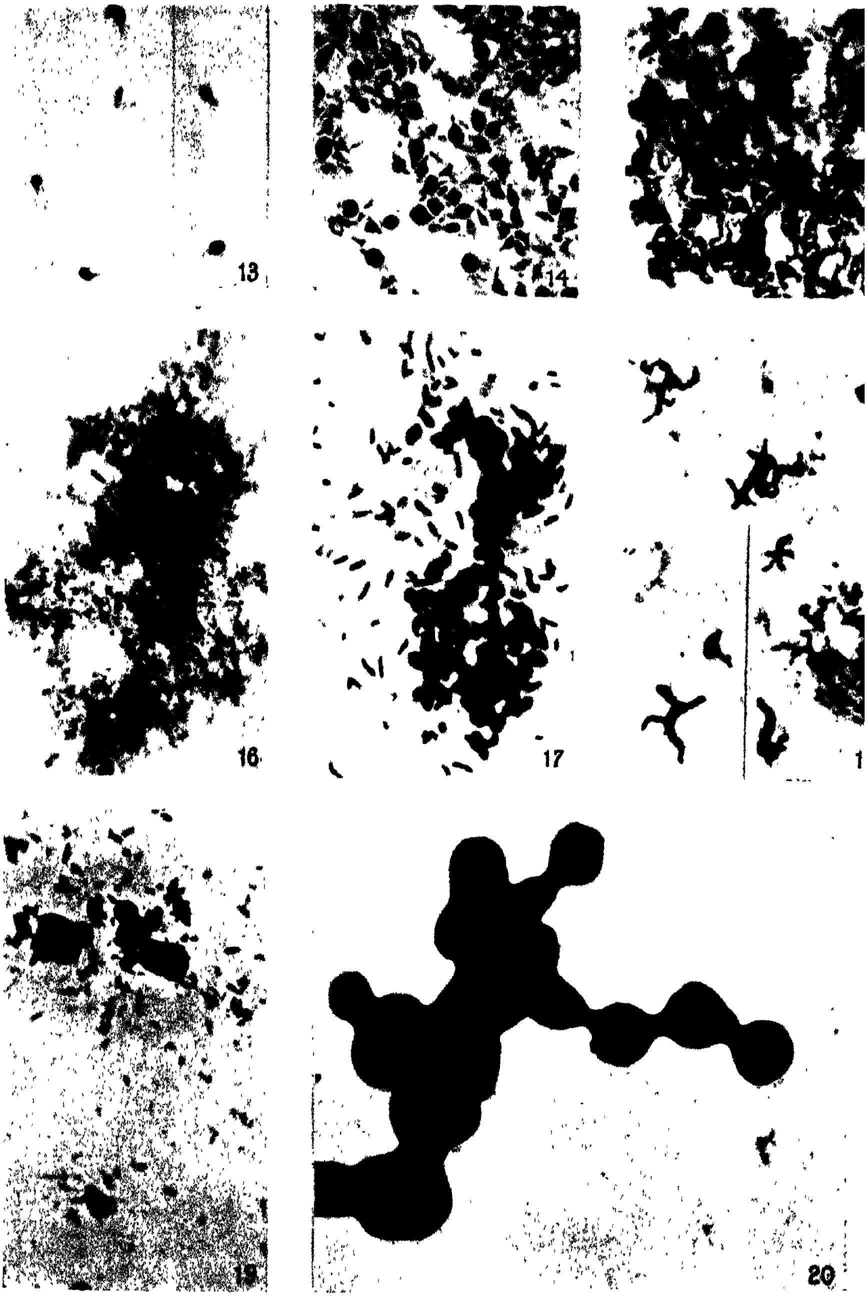
(8) Guilliermond, A. (1920). *The Yeasts.* Trans. by Tanner, F. W. New York.

(9) Lankester, E. R. (1876). *Quart. Journ. Microsc. Sci. N.S.* **16**, 27–40.

(10) Löhnis, F. (1905). *Centrbl. f. Bakt. II Abt.* **14**, 582–597.

(11) —— (1921). *Mem. Nat. Acad. Sci. Washington*, **16**, No. 2.


1
b
a
2
5
6
7
8
9
12


13
14
16
17
19
20

(12) Löhnis, F. and Hansen, R. (1921). *Journ. Agric. Res.* **20**, 543–555.
(13) Löhnis, F. and Smith, N. R. (1916). *Journ. Agric. Res.* **6**, 675–702.
(14) —— —— (1923). *Journ. Agric. Res.* **23**, 401–432.
(15) Nobbe, F. and Hiltner, L. (1893). *Landw. Vers. Stat.* **42**, 461.
(16) Prazmowski, A. (1890). *Landw. Vers. Stat.* **37**, 161–238.
(17) Schneider, A. (1902). *Bot. Gazette*, **34**, 109–113.
(18) Thornton, H. G. and Gangulee, N. (1926). *Proceed. Roy. Soc. London*, B, **99**, 427–451.
(19) Toenniessen, E. (1913). *Centrbl. f. Bakt. I Abt. Orig.* **69**, 391–412.
(20) —— (1914). *Centrbl. f. Bakt. I Abt. Orig.* **73**, 241–277.

(*Received August* 19*th*, 1927.)

SOIL TEMPERATURES IN EGYPT.

By E. McKENZIE TAYLOR, M.B.E., Ph.D., D.Sc., F.I.C.
(School of Agriculture, Cambridge.)

(With Nine Text-figures.)

Introduction.

The soil temperatures discussed in this paper were recorded at Giza primarily with the object of studying the temperature conditions in land during the period that it was formerly fallow under the basin system of irrigation and under the perennial system of irrigation before 1900. The soil temperatures were recorded throughout the year for a period of three years. The factors influencing soil temperatures in Egypt are not generally so complex as they are in England. In Egypt there is no rain during the greater portion of the year, cloud is practically absent from May to September, and the moisture content of an unirrigated soil reaches its minimum in May and remains at that minimum until November when the first of the winter rain may be expected in Cairo. At Giza the average annual rainfall is one inch. Variation in soil moisture content may be eliminated, therefore, from the factors determining the soil temperatures of an unirrigated bare fallow over the greater portion of Lower and Upper Egypt. Under these conditions, the soil temperatures were characterised by the similarity of corresponding periods from year to year. In this paper the soil temperatures for the year 1924 will be discussed.

The Observations.

The method of recording the soil temperatures in Egypt has been previously described (1). The temperatures were recorded by self-recording distance thermometers at the following depths: surface, 5 cm., 10 cm., 15 cm., 20 cm., 25 cm., 30 cm., 50 cm. and 100 cm. During the winter weeds were kept down by cutting close to the soil surface so as not to disturb the soil. Little trouble was experienced in controlling the weeds after the first winter as the heat during the summer effectively prevented a carry-over to the following winter. During the summer no weeds grew on the plot. The land was bare fallow throughout the period of observation. The following observations were also made: maximum and minimum air (screen) temperatures, black and white bulb thermometer tempera-

tures, amount of cloud, velocity and direction of wind, duration of sunshine. The moisture content of the soil in an adjoining fallow plot was also determined at weekly intervals at a series of depths.

General Remarks on the Soil Temperature Curves.

The types of the soil temperature curves obtained at some of the depths are shown in Fig. 1. Curves for the coolest and hottest parts of the year, in January and July respectively, are shown for comparison.

The Surface Temperatures.

It will be seen that the trace of the surface temperatures is divisible into three parts. There is a sharp break in the curve at the minimum temperature. This occurs at sunrise, the soil temperature commencing to rise to its maximum for the day. The rise is rapid, the maximum being sharply defined. The maximum surface temperature on cloudless days occurred at the same time throughout the year. After the maximum has been passed, a rapid fall in temperature takes place until sunset. At sunset, there is again a sharp break in the curve, the curve between this point and sunrise representing the cooling of the soil due to radiation. The highest surface soil temperatures were recorded in July and the lowest in January. The average amplitude of the daily wave of temperature at the surface in January is about 21° C. and in July it exceeds 40° C.

The Soil Temperatures at 5 cm.

At 5 cm. the curve is divisible into three portions similar to the surface curve. The breaks in the curve at sunrise and sunset are not so sharp as those in the surface curve. The amplitude of the temperature wave at this depth is less than the surface amplitude and the times of maximum and minimum lag behind those at the surface. During July the amplitude of the temperature wave at this depth is about 24° C. and in January it is 13° C. The highest and lowest temperatures were recorded in July and January respectively on the same dates as those at the surface.

The Soil Temperatures at 10 cm.

There is a marked difference between the form of the curve for the temperature at 10 cm. and those for the surface and 5 cm. depths. The curve is no longer divisible into three portions but only into two main portions representing the heating and cooling of the soil at this depth. The divisions between the heating and cooling portions of the curve are

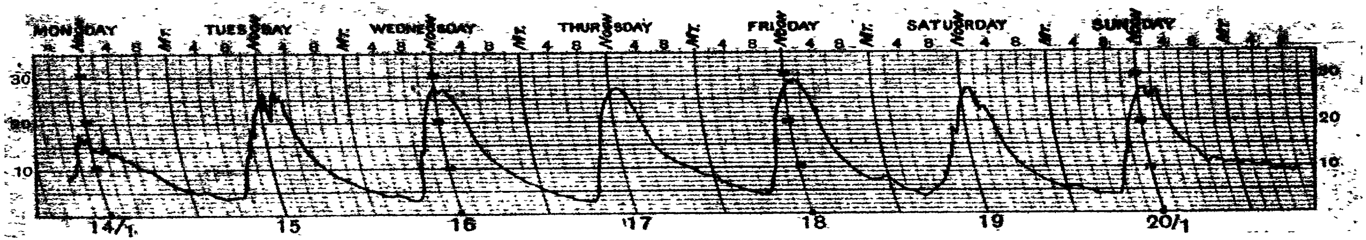


Fig 1 *a*. Surface. Trace, January, 1924.

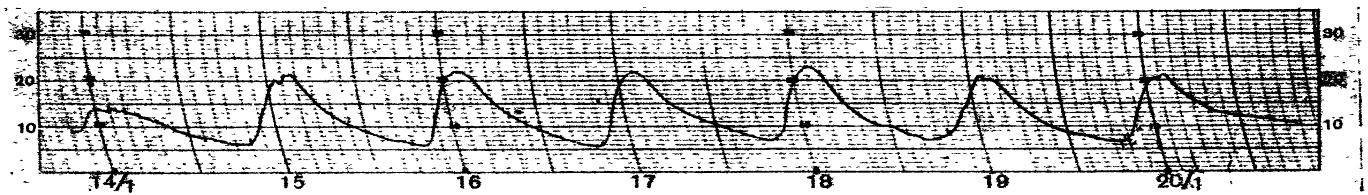


Fig. 1 *b*. 5 cm. Trace, January, 1924.

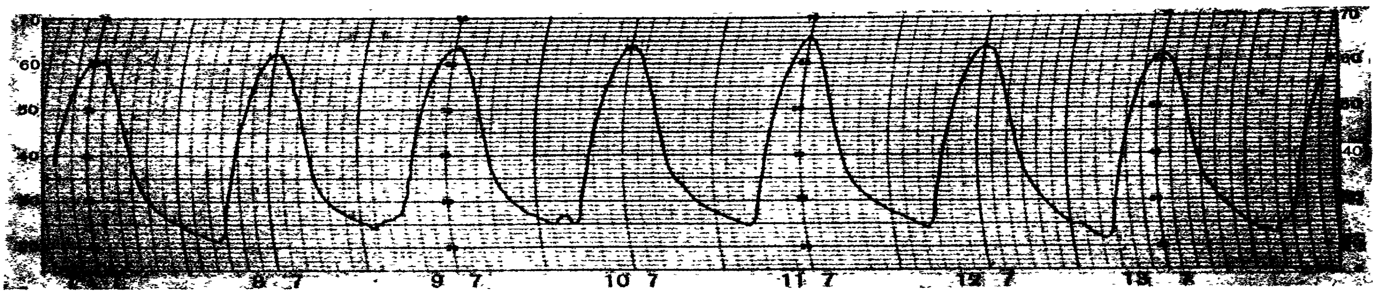


Fig. 1 *c*. Surface. Trace, July, 1924.

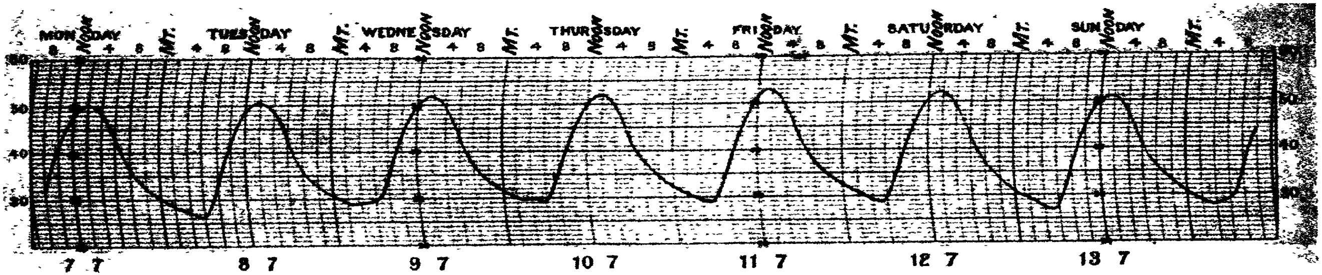


Fig. 1 *d* 5 cms. Trace, July, 1924.

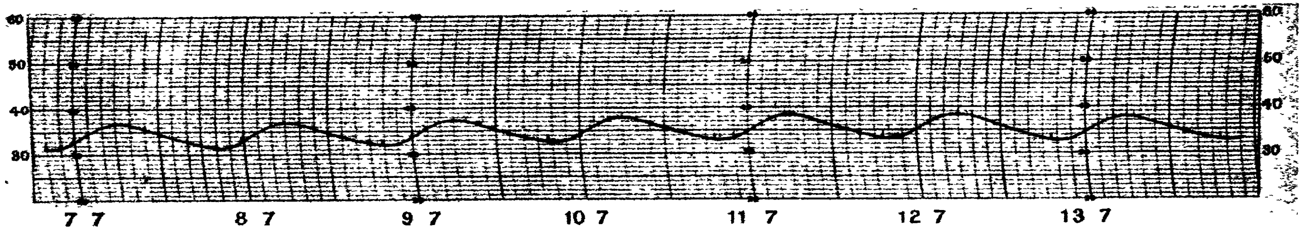
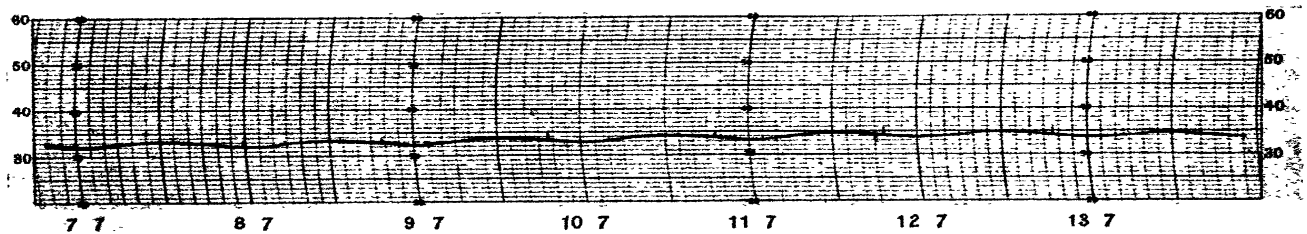


Fig. 1 *e*. 15 cms. Trace, July, 1924.



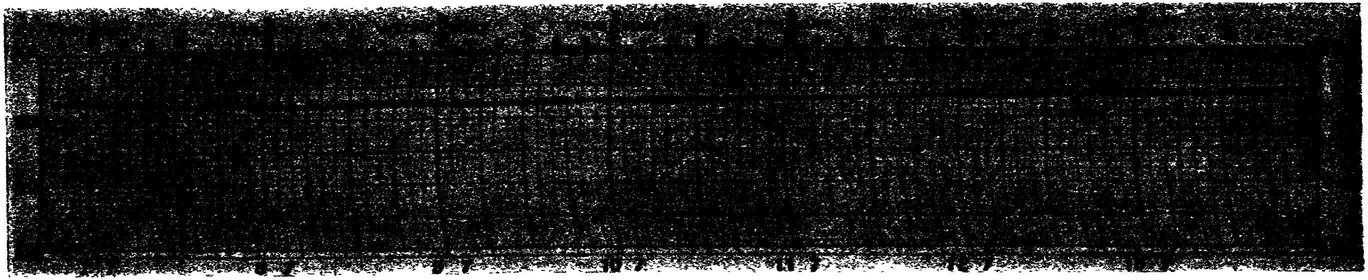


Fig. 1 *g*. 50 cms. Trace, July, 1924.

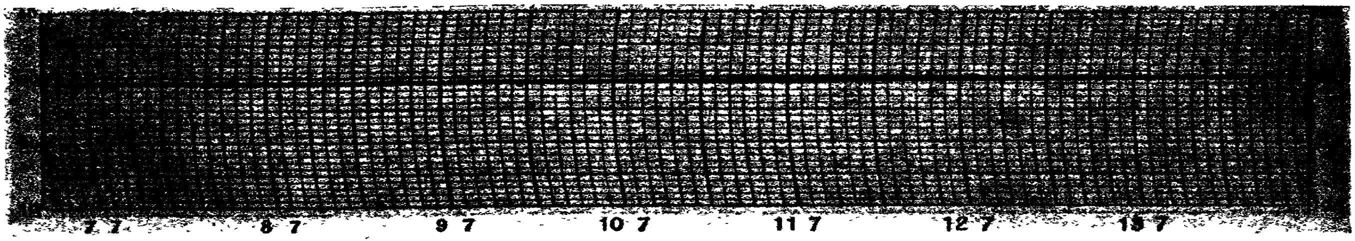
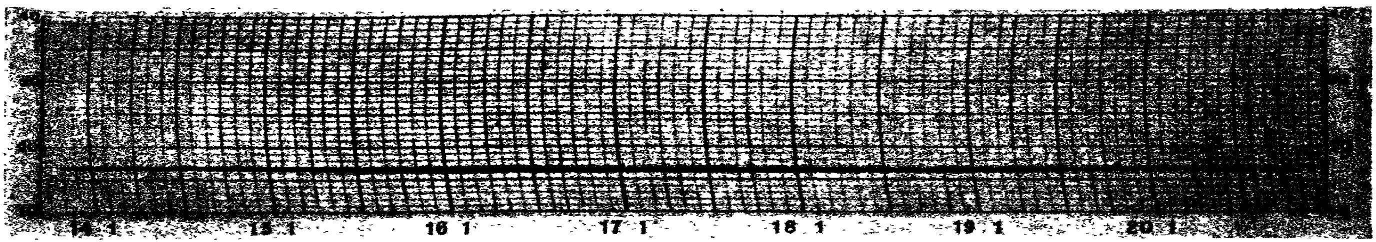


Fig. 1 *h*. 100 cms. Trace, July, 1924.



no longer sharp but there is a gradual transition both from heating to cooling and from cooling to heating. The amplitude of the temperature wave is considerably reduced, being greatest in July and least in January. Minor events, such as the passing of a cloud, affecting the surface and 5 cm. soil temperatures are no longer recorded at this depth. The temperature wave has been considerably damped and it shows a further lag in the time of maximum and minimum temperatures.

The temperature curves at 15 cm., 20 cm., 25 cm. and 30 cm. are similar in general characteristics to that at 10 cm. The damping of the wave is increased with depth and the lag in the time of maximum and minimum temperatures also increases with depth.

THE SOIL TEMPERATURES AT 50 CM.

The soil temperatures at 50 cm. are still subject to a daily variation and exhibit a daily maximum and minimum. The amplitude of the daily wave at this depth did not exceed 0·5° C. and was about 0·2° C. in January. The highest temperature at this depth, 33·5° C., was recorded on August 15. The daily temperature wave at this depth commences to resemble the annual temperature waves beyond the zone of daily variation and exhibits a seasonal lag in reaching its maximum temperature.

THE SOIL TEMPERATURES AT 100 CM.

No daily variation in temperature could be detected at a depth of 100 cm. even when the amplitude of the temperature wave at the surface exceeded 40° C. The variation probably did occur but was too small to be recorded on the instrument. Theoretically, it should be of the order of 0·005° C. The temperatures at this depth present a well-defined seasonal maximum and minimum. The maximum temperature of 31° C. was recorded on August 31 and the minimum temperature of 16·5° C. on January 18.

It will be seen that the soil temperatures are subject to considerable daily variation near the surface, to variation with depth, and to seasonal variation. The type and magnitude of these variations indicate that it is impossible to express the soil temperature conditions as the result of a daily observation at a particular depth at a specified time. Again, the most important soil zone, from the biological point of view, is that which is subjected to the greatest daily variations in temperature and in which, therefore, the single observation would be of least value. It will be further seen that mean temperatures, $\frac{(\text{max.} + \text{min.})}{2}$, are of little value in defining

the soil temperature conditions in the zone of daily variation. For instance, the mean temperature at the soil surface in July was 41·5° C. and at 10 cm. depth was 34·6° C. These figures convey no idea of the difference in temperature conditions at the two depths in the soil from the biological standpoint. At the surface in July, the mean maximum temperature, 61·3° C., is well above the optimum for bacterial activity, while the mean maximum at 10 cm., 38·2° C., is very near the recognised optimum. From a biological aspect, mean temperatures, $\frac{(\text{max.} + \text{min.})}{2}$, are as misleading as a daily observation at an arbitrarily chosen time.

A Comparison of Air and Soil Temperatures.

The maximum and minimum soil temperatures at the various depths and the maximum and minimum air (screen) temperatures are shown as monthly means, calculated from the daily observations, in Table I.

Table I. *Monthly mean maximum and minimum soil and air temperatures (degrees centigrade).*

	Surface		5 cm.		10 cm.		15 cm.		20 cm.		25 cm.		30 cm.		Air	
Month	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Jan.	25·5	3·9	19·8	6·7	15·1	10·6	14·5	11·2	14·3	11·9	14·2	13·2	14·5	13·8	18·8	5·3
Feb.	33·6	6·0	25·4	9·2	18·7	13·2	17·8	13·5	16·9	14·0	16·5	15·1	16·3	15·4	23·0	6·9
Mar.	37·9	9·2	29·6	12·6	22·6	16·3	21·6	16·9	20·8	17·4	19·6	18·0	19·4	18·4	24·0	9·0
April	48·3	11·7	37·1	16·7	28·4	21·2	27·2	21·7	26·2	22·2	24·6	22·9	24·2	23·0	29·7	10·6
May	55·4	14·9	43·1	20·2	32·6	25·2	31·4	25·8	30·1	26·0	28·5	26·6	28·0	26·7	31·6	13·4
June	59·8	19·7	48·2	24·8	36·7	29·6	35·2	30·0	33·9	30·1	32·5	30·8	31·9	30·8	35·5	18·3
July	61·3	21·2	50·1	26·1	38·2	31·1	36·7	31·4	35·7	32·0	34·2	32·4	33·6	32·5	36·2	19·6
Aug.	59·4	20·9	49·3	25·6	37·8	30·8	36·3	31·2	35·2	31·7	34·1	32·3	33·6	32·5	36·5	19·3
Sept.	55·2	18·9	45·7	23·5	35·3	29·1	34·1	29·5	33·3	30·1	32·4	30·9	32·1	31·1	34·3	17·9
Oct.	47·2	14·9	39·0	19·1	30·3	24·7	29·3	25·3	28·8	26·1	28·3	27·1	28·2	27·4	31·0	15·1
Nov.	37·4	9·6	30·5	13·5	23·7	19·1	23·4	19·8	23·2	21·0	22·9	21·9	23·0	22·4	25·4	10·7
Dec.	31·6	6·3	24·8	9·7	18·8	14·9	18·3	15·4	18·2	16·1	18·1	17·2	18·4	17·9	21·5	7·7

The maximum temperature at the surface of the soil is always considerably above the maximum air temperature though the difference is less marked in winter than in summer. It will be seen that the maximum soil temperature at any depth cannot be directly inferred from the maximum air temperature. In October the maximum air temperature is approximately the same as the maximum temperature at a depth of 10 cm. From November to April the maximum air temperature is higher than the maximum temperature at 10 cm., while from May to September the maximum air temperature is below the soil temperature at 10 cm. The maximum air temperatures were recorded in May, but the soil temperatures to a depth of 30 cm. did not reach their seasonal maxima until July. The highest surface soil temperature recorded during

1924 was 64·0° C. on July 12, the maximum air (screen) temperature on that date being 40·8° C. The time at which the daily maximum temperature of the surface soil is reached is constant throughout the year on clear days at 1 p.m. The time of maximum air temperature is usually about 3 p.m.

From October to February the minimum temperature of the surface soil is generally below the minimum air temperature. The minimum temperature of the surface soil is generally above the minimum air temperature from March to September. During the daily cooling period after sunset, the surface soil is receiving heat from the layers of soil below. The temperature gradient in the soil layers below the surface is much steeper in the summer than in the winter. As a result, the rate at which heat is conducted to the surface from the soil layers below the

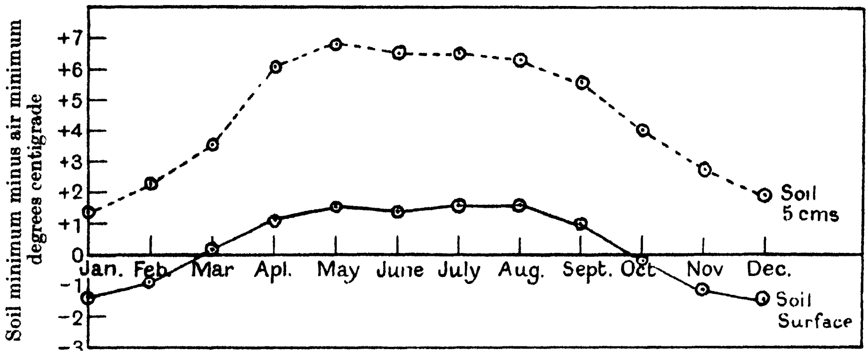


Fig. 2. Difference between minimum temperatures of soil and air.

surface is greater in summer than in winter. The minimum soil temperature in the summer is thus maintained higher than the minimum air temperature. During the winter the soil temperature gradient is less steep and, hence, the rate at which heat is conducted to the surface from the layers below is insufficient to maintain the minimum soil surface temperature above the minimum air temperature. On July 11, at the time of minimum soil surface temperature, the temperature at a depth of 5 cm. was 5° C. higher than the temperature at the surface. On January 17 the temperature at a depth of 5 cm. at the time of soil surface minimum was only 2° C. above the soil surface temperature. The rate of flow of heat from a depth of 5 cm. to the surface would, therefore, be higher in July than in January. As a result, the minimum temperature at the soil surface would be maintained higher with reference to the minimum air temperature in July than in January.

The minimum soil temperatures at greater depths than 5 cm. are

always above the minimum air temperatures. The difference between the minimum soil temperature at any depth and the minimum air temperature is not constant throughout the year. In Fig. 2 are plotted the differences between the minimum soil surface temperature and the minimum air temperature, and also between the minimum 5 cm. soil temperature and the minimum air temperature from the monthly means for these observations. It will be seen that the differences between the minimum soil temperatures and the minimum air temperature are not constants, being greatest in summer and least in January.

No relation appears to exist between the minimum air temperature and the minimum soil temperature at any depth. The minimum soil temperature at any depth is not only determined by the radiation of heat from the soil surface but also by the rate at which heat is conducted to the surface from the soil layers below.

The Zone of Daily Variation in Soil Temperature.

From the records in Table I, it will be seen that the amplitude of the daily temperature wave is rapidly reduced as it penetrates the soil. Under the conditions of maximum amplitude at the surface, a daily variation of 0·5° C. was recorded at a depth of 50 cm. but no effect due to the daily wave of temperature could be detected at 100 cm. Fig. 1 *g* and Fig. 1 *h* show the type of trace obtained at 50 cm. and 100 cm. during one week in July. A daily variation in temperature is noticeable at 50 cm. but this is superimposed on the seasonal wave which at this period is rising towards its maximum. At 100 cm. the curve shows no daily variation but a gradual rise in temperature throughout the week. From observations on sand temperatures (2) in the desert in Egypt, it has been shown that the daily range in temperature at a depth of 96·9 cm. would be about one-thousandth of a degree centigrade. The instruments used in this investigation were unable to detect variations of this order. From these results, it appears that the daily range in temperature at 100 cm. below the surface is so small that this depth can be regarded as the limit of the zone of daily variation in soil temperature. Below this depth the soil temperatures are mainly influenced by the annual temperature wave. As will be shown later, the depth of the zone of daily variation in soil temperature varies with season, but the magnitude of the temperature changes at 100 cm. are always small so that the alteration of the depth with season does not seriously affect the above conclusion.

THE AMPLITUDES OF THE TEMPERATURE WAVES IN SOIL AND AIR.

The amplitudes of the soil temperature waves at various depths and of the air temperature wave are shown in Table II.

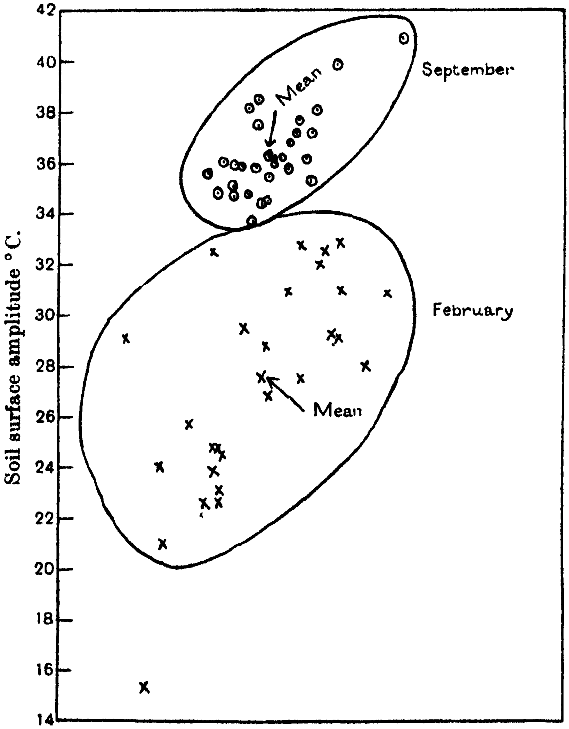
Table II. *Monthly means of amplitudes of daily temperature waves in soil and air (degrees centigrade).*

Month	Surface	5 cm.	10 cm.	15 cm.	20 cm.	25 cm.	30 cm.	Air
Jan.	21·6	13·1	7·7	4·2	2·4	1·0	0·7	13·5
Feb.	27·6	16·2	9·7	5·5	2·9	1·4	0·9	16·1
Mar.	28·7	17·0	10·3	6·0	3·4	1·6	1·0	15·0
Apr.	36·6	20·4	11·4	6·5	4·0	1·7	1·2	19·1
May	40·5	22·9	12·8	7·4	4·1	1·9	1·3	18·2
June	40·1	23·4	13·5	7·8	3·8	1·7	1·1	17·2
July	40·1	24·1	14·3	8·5	3·7	1·8	1·1	16·6
Aug.	38·5	23·7	14·2	8·3	3·5	1·8	1·1	16·8
Sept.	36·3	22·2	13·0	7·5	3·2	1·5	1·0	16·4
Oct.	32·3	19·9	11·8	7·0	2·7	1·2	0·8	15·9
Nov.	27·8	17·0	10·2	5·9	2·2	1·0	0·6	14·7
Dec.	25·3	15·1	8·9	5·3	2·1	0·9	0·5	13·8

The maximum amplitude of the air temperature wave occurs in April, the minimum amplitude occurring in January. The amplitudes of the soil temperature waves remain approximately constant during May, June and July and are at their maximum during this period. The minimum amplitudes of the soil temperature waves at the surface, 5 cm., 10 cm. and 15 cm. depths occur in January at the same time as the minimum air amplitude. At 20 cm., 25 cm. and 30 cm. the minimum amplitudes were recorded in December. As will be shown later, this is probably due to the influence of the annual wave below the zone of daily variation. During December passage of heat upwards from the zone of annual variation is taking place and maintains the minimum temperatures at certain depths in the zone of daily variation at an artificially high minimum with respect to the daily temperature wave at the surface of the soil.

There appears to be no relation between the amplitude of the air temperature wave and the amplitude of the soil temperature waves. The soil temperature amplitudes are considerably influenced by the annual temperature wave. The soil temperature amplitudes on the rising portion of the annual temperature wave are smaller than those on the falling portion of the annual temperature wave for similar amplitudes of the air temperature wave. This is illustrated by the comparison of the soil amplitudes for February and September. The air temperature amplitude in February is approximately the same as the air temperature amplitude in September as indicated by the monthly means. The soil surface temperature amplitude in February is, however, much less than

the soil surface temperature amplitude in September. In Fig. 3 the daily soil surface temperature amplitudes have been plotted against the corresponding air temperature amplitudes for September and February. It will be seen that the combination of temperature amplitudes falls into two distinct groups. The surface soil temperature amplitude in September is much higher than in February for a given air temperature amplitude. It follows, therefore, that the factors affecting the amplitude of the temperature wave at the surface of the soil are different from those determining the amplitude of the air temperature wave.



Air amplitude °C.

Fig. 3.

The relation between the reduction in the amplitude of the soil temperature wave with increase in depth has been developed from a consideration of the amplitudes of the annual waves at depths below the zone of daily variation in temperature. Briefly stated the relationship is that the amplitude of the temperature wave decreases in geometrical progression as the depth increases in arithmetical progression. In the

surface layers of the soil the conditions are much less uniform than at depths below the zone of daily variation in soil temperature. The physical problem in connection with the surface layers of soil is the propagation of short period heat waves of variable phase into an unevenly heated body of variable specific heat and conductivity. Rambaut (3), discussing the soil temperature observations at Oxford, says of the 6·5-inch thermometer, "I have omitted the results derived from the reading of No. 1 (6·5-inch), as they seem too much affected by short period variations to afford reliable results. This thermometer, too, is buried in a surface soil of quite different character from the sandy gravel containing the other thermometers." As the phase of the short period waves alters with season, depth, and the direction of the movement of heat represented by the annual wave, it would be impossible to determine on what portion of the daily temperature wave his single observation was situated. Further, as the observation was made at a specified time daily, they would be situated at continually varying positions on the daily temperature wave owing to the variation of the phase of the wave with season. From the series of observations in Egypt it is possible to determine whether a similar relationship holds in the zone of daily variation to that which has been shown to exist beyond the zone of daily variation. The reduction ratios of the amplitudes of the temperature waves with increase in depth are shown in Table III.

Table III. *Reduction ratios of soil temperature wave with increasing depth.*

Month	Surface–5 cm.	5–10 cm.	10–15 cm.	15–20 cm.	20–25 cm.	25–30 cm.
Jan.	·60	·34	·73	·73	·42	·70
Feb.	·59	·34	·78	·68	·48	·64
Mar.	·60	·37	·76	·72	·47	·63
Apr.	·56	·35	·76	·73	·43	·71
May	·56	·32	·75	·73	·46	·68
June	·58	·30	·73	·73	·45	·65
July	·60	·30	·75	·70	·49	·61
Aug.	·62	·30	·73	·70	·53	·61
Sept.	·61	·28	·74	·70	·47	·66
Oct.	·61	·28	·71	·68	·44	·66
Nov.	·61	·27	·72	·66	·45	·60
Dec.	·60	·26	·74	·72	·43	·55

From Table III it will be seen that the ratio of the amplitudes of the temperature waves between any two depths separated by an interval of 5 cm. is practically constant throughout the year. The greatest variation is shown in the ratio between the 25 cm. and 30 cm. depths. As the amplitudes of the waves at these depths are small, a very small error in

reading the temperature at these depths would cause a big variation in the ratio of the amplitudes.

While the ratios between the amplitudes of the temperature waves at any two depths is constant throughout the year, the ratió between the amplitude of the temperature waves is not constant throughout the depth of soil under observation. In this respect the propagation of a temperature wave into the surface layers of the soil differs from the propagation of the annual wave into the soil beyond the zone of daily variation in temperature. From the theoretical consideration of the propagation of a temperature wave there should be a constant reduction ratio with increase in depth in the zone of daily variation in temperature; the soil conditions in this zone, therefore, exert some effect on the propagation of the wave.

The two main factors determining the propagation of the wave are the conductivity and specific heat of the soil. The main cause of variation of the specific heat and conductivity of the soil is its moisture content. This, in turn, will be dependent to some extent upon the mechanical composition of the soil. The mechanical analyses of the soil at the various depths at which observations were taken are shown in Table IV.

Table IV. *Mechanical composition of soil at various depths (per cent.).*

Depth (cm.)	Gravel	Coarse sand	Fine sand	Silt	Clay
5	—	3·3	58·5	20·4	16·7
10	—	1·9	57·9	18·1	21·2
15	—	2·1	60·2	19·8	17·1
20	—	1·5	48·4	29·0	19·2
25	—	2·3	47·9	30·2	18·7
30	—	3·3	50·8	26·1	18·3

Table V. *Percentage moisture content of soil at various depths.*

Depth (cm.)	Moisture (%)	Depth (cm.)	Moisture (%)
2·5	3·0	22·5	13·6
7·5	5·3	27·5	16·0
12·5	10·0	50	18·4
17·5	13·1	100	20·5

It will be seen that the soil has not a uniform mechanical composition. There is an increase in the clay content at 10 cm. This is the normal depth of ploughing in Egypt, and it seems probable that under the intensive irrigation now practised some of the clay particles may have been washed down from the layers of soil above and accumulated at this depth. An increase in the clay content of the soil would increase its water retaining powers and, hence, increase its specific heat. This would have the effect

of reducing the amplitude of the temperature wave at this depth beyond the theoretical amount calculated from a consideration of depth alone.

A series of weekly determinations of moisture at various depths in the soil was made throughout the fallow period. These demonstrate further the variable character of the material through which the daily temperature wave is propagated. The results of the series of moisture determinations on May 21 are shown in Table V.

The moisture content of the soil increases rapidly with increase in depth in the first 12·5 cm. of soil, after which the rate of increase is much slower. From the reduction ratios of the amplitudes of the temperature waves, it seems that the increase in moisture content down to a depth of 12·5 cm. increases the specific heat of the soil without increasing to any extent its conductivity. Between 12·5 cm. and 22·5 cm. the increase in moisture content appears to increase the conductivity of the soil. The further increase in water content between 22·5 cm. and 27·5 cm. appears to reduce the conductivity of the soil as the ratio of the amplitudes falls from 0·7 to 0·45.

The variable character of the soil as regards specific heat and conductivity causes considerable variation in the ratio of the amplitudes of the temperature waves over a succession of depths, though between any two depths the ratio, in the absence of rain, appears to be constant throughout the year.

The propagation of a temperature wave into desert sand has been dealt with previously (2). It was shown that, as the moisture content of the desert sand was practically constant throughout the zone of daily variation in temperature, the conductivity and specific heat of the sand remain constant throughout the zone, and that there is a constant reduction in the ratio of the amplitudes of the temperature waves with constant increases in depth. As the desert sand and the soil were under similar meteorological conditions, the variable reduction ratio of the amplitudes in the soil must be attributed to the variability of the physical properties of the soil.

THE LAG IN THE TIME OF MAXIMUM TEMPERATURE WITH DEPTH.

The time of maximum surface soil temperature is, in the absence of clouds, determined by the time at which the sun reaches its meridian. As this is constant throughout the year, the time at which the maximum temperature of the surface soil is reached is also constant throughout the year. This is confirmed by the soil temperature records. In the absence of cloud, the maximum surface temperature was recorded at 1 p.m.

throughout the year. As the temperature wave is propagated into the soil, the times of maximum temperature at depths below the surface will lag behind the time of surface maximum. This time lag will increase with depth. As the time of maximum temperature at the surface is constant, the times of maxima at depths below the surface will also be constant. An examination of the records shows that on a clear day this is the case. The times at which the maximum temperatures are recorded at the various depths are shown in Table VI.

Table VI. *Times of maximum soil temperature at various depths.*

Depth (cm.)	Hours	Depth (cm.)	Hours
Surface	13·00	20	21·00
5	14·45	25	23·00
10	17·00	30	1·00
15	19·00	50	9·00

For each increase in depth of 5 cm., the lag in the time of maximum temperature increases by two hours and occurs at a constant time throughout the year.

If the times of maxima are plotted against depth, as has been done in Fig. 4, it will be found that they lie on a straight line. The time lag of the maximum temperature at any depth behind the time of maximum at the surface is given by the equation

$$\text{time lag} = \frac{d}{\tan A}$$

where d is the depth, and A is the angle which the line of maxima makes with the horizontal.

For Egypt, $A = 68^\circ\ 12'$, so that the time of soil maximum temperature in Egypt at any depth is given by the equation

$$\text{time of maximum temperature} = 13 + \frac{d}{\tan 68^\circ\ 12'}.$$

The angle of the lag of maximum will vary with the diffusivity of the soil, but the variation appears to be small. For desert sand the angle of the lag of maximum was 69°. Experiments will be necessary before it can be determined whether the equation is applicable to other countries. It is suggested, however, that as the lag in the maximum is essentially a soil factor the equation will be capable of general application.

The Lag in the Time of Minimum Temperature with Depth.

The time of minimum temperature of the surface soil occurs just before sunrise in the absence of cloud. As the time of sunrise varies with the season of the year, the time of minimum temperature of the surface

soil is also variable. Since the time of minimum temperature at the soil surface varies, the times of minimum soil temperature at depths below the surface must also be variable. This is found to be the case. Table VII shows the times of minimum temperature at various depths on clear days in July and January.

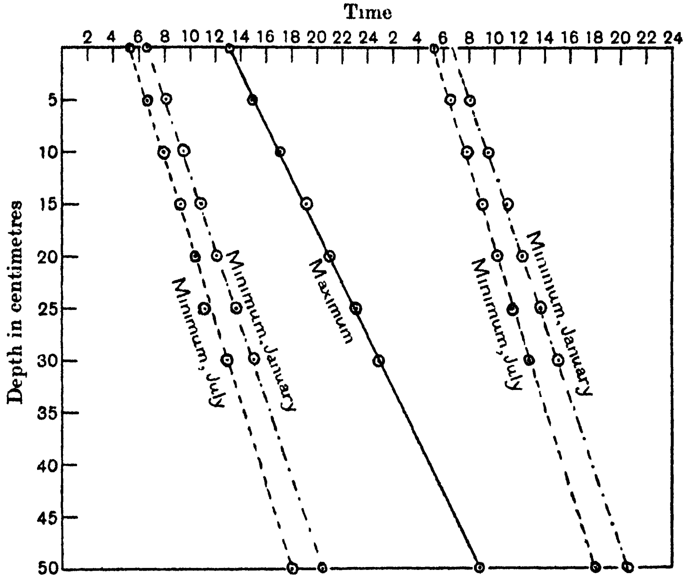


Fig. 4. Times of maximum and minimum in July and January.

Table VII. *Times of minimum soil temperature at various depths.*

Depth (cm.)	July Hours	January Hours
Surface	5·15	6·45
5	6·30	8·00
10	8·00	9·15
15	9·15	10·45
20	10·15	12·00
25	11·15	13·45
30	12·30	15·00
50	18·00	20·15

The lag in the time of minimum temperature increases with increase in depth, the amount of lag behind the time of surface minimum at a depth of 50 cm. being approximately 13 hours. When plotted, the times of minimum temperature lie approximately on a straight line and, hence, the time lag can be expressed by the equation for a straight line. There is considerable variation in the position of the line of minimum temperature. The minimum temperature at the surface in January is $1\frac{1}{2}$ hours

later than in July. As a result of this variation in the time of minimum temperature, there is an alteration in the lengths of the heating and cooling portions of the temperature wave with season. In summer the time between minimum and maximum is longer than in winter.

The lines of the times of minimum in summer and winter are not exactly parallel, but for the surface layers they can be considered as parallel without any great error. The equation representing the time of minimum at any depth in the soil in Egypt will be

$$\text{time of minimum} = \text{hour of sunrise} + \frac{d}{\tan A}$$

where d = depth, and A = the angle which the line of minimum makes with the horizontal.

For Egypt this equation can be written

$$T = \text{hour of sunrise} + \frac{d}{\tan 76^\circ}.$$

The lag in the time of minimum with increase in depth is approximately the same in the desert as in the soil. The equation appears, therefore, to be generally applicable to Egypt. The angle which the line of the times of minimum makes with the horizontal will vary with the diffusivity of the soil. From a comparison of the observations in the desert and in the soil at Giza, it appears that this variation will be small. It is suggested, therefore, that the equation is capable of general application.

A Substitute for a Series of Continuous Recording Thermometers.

The expense of installing a series of thermographs suitable for recording soil temperatures is considerable. The present method of recording soil temperatures is admittedly unsatisfactory as it consists of taking one or two observations a day at specified times. As will be seen from the records under discussion, these isolated observations represent variable portions of the temperature wave according to season and, hence, it is impossible to interpret them correctly. If the times of minima were constant, these isolated observations would be comparable. As, however, at one season of the year the observation may be on the cooling portion of the temperature wave and at another season on the heating portion of the wave they do not give a correct record of the variations in soil temperature at a particular depth. Again, as the times of minimum and maximum vary with depth, the observations at arbitrarily selected times give no information of the variation in temperature conditions experienced by a soil during the day.

From the records discussed in this paper it appears that correct information as to the temperature waves could be obtained at comparatively little expense. As the times of maxima lie on a straight line and as the position of the line of maxima is constant throughout the year, the installation of two thermographs at different depths would give the line of maxima. The maximum soil temperatures at other depths could then be taken by means of ordinary thermometers at the times indicated by this line of maxima.

As the minimum soil temperature occurs just before sunrise, and as the lines of minima, although variable, are approximately parallel throughout the year, the times at which ordinary thermometers at various depths should be read would be indicated by a line joining the hour of sunrise with the hour of minimum temperature at one depth below the surface as shown by one recording thermometer. The variation in the time of reading the thermometers to determine the times of minimum temperature could be calculated readily from the variation in the hour of sunrise.

ALTERATIONS IN THE PHASE OF TEMPERATURE WAVE.

Three types of alteration in the phase of the daily temperature waves in the soil occur: (*a*) an alteration with season, (*b*) an alteration with depth, and (*c*) an alteration due to the direction of heat flow in the soil beyond the zone of daily variation in temperature.

If the lines of maxima and minima at the various depths are plotted, it will be seen that, while each lie on straight lines, the lines are not parallel. The line of maximum temperature remains in the same position throughout the year. The line of minimum temperature is not constant but varies with the hour of sunrise and, hence, has a seasonal variation in position. These lines have been plotted in Fig. 4 for a clear day in July and a clear day in January, the times of earliest and latest sunrise. The lines of minima have been repeated in the figure.

(*a*) *The alteration in the phase of the temperature waves with season.*

The daily duration of the periods of heating and cooling at various depths in July and January are shown in Table VIII.

The alteration in phase of the temperature waves caused by the later time of sunrise in winter has resulted in a reduction in the length of the heating period and an increase in the length of the cooling period at each of the depths. In July at only 27 cm. depth the length of the heating period of the soil is equal to the length of the cooling period. In January

the depth of equal lengths of the heating and cooling periods is 45 cm. As a result of this variation in the lengths of the heating and cooling periods in the soil with season, it will be seen that it is impossible to infer from one observation of soil temperature at a particular depth, at an arbitrarily chosen time, the temperature conditions before and after the time of observation.

Table VIII. *Duration of heating and cooling periods of the soil (hours).*

Depth (cm.)	July		January	
	Heating	Cooling	Heating	Cooling
Surface	7¾	16¼	6¼	17¾
5	8¼	15¾	6¾	17¼
10	9	15	7¾	16¼
15	9¾	14¼	8¼	15¾
20	10¾	13¼	9	15
25	11¾	12¼	9¼	14¾
30	12½	11½	10	14
50	15	9	12¾	11¼

The result of the seasonal alteration in phase of the temperature wave may be stated as follows: the later the sunrise, the shorter is the heating period and the longer is the cooling period of the daily wave of soil temperature.

(b) The alteration in phase of the temperature wave with depth.

Fig. 4 shows that the lines of the times of maxima and minima are not parallel, the lag in the time of minimum at any depth not being so great as the lag in the time of maximum for the same depth. As a result, the duration of heating and cooling varies with the depth. The duration of heating increases with increase in depth. The duration of cooling decreases with increase in depth. There is, therefore, an alteration of the phase of the temperature wave with depth. For instance, in July at 10 cm. depth the length of time between minimum and maximum is nine hours and between maximum and minimum 15 hours. These times are reversed at a depth of 50 cm., the time between minimum and maximum being 15 hours and between maximum and minimum nine hours.

Keen and Russell (4) comparing the records of the 6 in. soil thermometer at Rothamsted with the records of the 10 in. thermometer obtained by Callendar at the McGill University, Montreal, state, "Between his results and ours, however, there is an interesting difference in detail; in our case the rise of temperature at 6 in. depth is rapid and the fall slow; in his the rise at 10 in. depth is slower than the fall...."

The explanation of this difference is that the temperature wave alters its phase with increasing depth owing to the lines of maximum and

minimum not being parallel. The phase of the wave at a depth of 6 in. at Rothamsted has not altered to the extent that the heating portion is longer than the cooling. In the case of the 10 in. thermometer at Montreal, the phase has altered to such an extent that the heating period has become longer than the cooling.

The results obtained in Egypt at the 6 in. and 10 in. depths are interesting in view of the above comparison. At the 6 in. depth (15 cm.) the heating portion of the wave is shorter than the cooling portion, agreeing with the Rothamsted observations. At 10 in. depth (25 cm.) the heating portion is still shorter than the cooling portion. In summer at a depth of 27 cm. the duration of heating is equal to the duration of cooling, *i.e.* 12 hr. each. At depths lower than 27 cm. the duration of heating exceeds the duration of cooling.

The depth at which the duration of heating is equal to the duration of cooling is 27 cm. in July. In January at this depth, the length of the heating portion of the curve is approximately 10 hr. and the cooling portion 14 hr. The depth at which the duration of heating is equal to the duration of cooling in January is about 45 cm. Beyond a depth of 45 cm. in January, the duration of heating exceeds the duration of cooling.

It will be seen, therefore, that the phase of the temperature wave alters with depth, an increase in depth being accompanied by an increase in the duration of heating and a corresponding decrease in the duration of cooling.

(c) *The alteration in phase of the daily wave due to the annual temperature wave.*

It will be noticed in Fig. 4 that the lines of the times of minimum in January and July are not quite parallel. The lag in the minimum temperature at a depth of 50 cm. behind the time of minimum at the surface in January as compared with July has increased by a greater amount than the difference in the times of minimum at the surface in these two months. This phenomenon has been previously noticed in connection with the desert sand temperatures (2). The explanation offered was that the minimum temperature in winter at a depth of 20 cm. is below the temperature at 100 cm. (this depth being approximately the limit of the zone of daily variation in soil temperature). In the winter, therefore, at the time of minimum temperature at a depth of 20 cm. there will be a passage of heat from below upwards tending to maintain the minimum temperature at a depth of 20 cm. higher than it theoretically should be as determined by the surface soil minimum. In summer the temperature

at 100 cm. is below the minimum at a depth of 20 cm. and, hence, there will be a passage of heat downwards from a depth of 20 cm. at the time of minimum temperature. This will tend to make the minimum temperature at a depth of 20 cm. in summer lower than should theoretically be the case as determined by the surface minimum. As the time of minimum temperature at any depth is dependent upon the time of arrival at that depth of the heating wave, it will be seen that as the minimum tends to be higher than it theoretically should be in March, the wave of heat from the surface will have to reach a higher temperature than it theoretically should do before it can bring about the change from cooling to heating. To reach this higher temperature it will take longer and, hence, the minimum temperature will occur later in winter than would be expected from a consideration of the daily wave. In summer the reverse is the case, the minimum occurring earlier than would be expected. It appears that the lag in the time of minimum temperature in the zone of daily variation is to some extent dependent upon the direction of heat movement in the soil below the zone of daily variation.

The Seasonal Alteration in the Depth of the Zone of Daily Variation in Temperature.

The limit of the zone of daily variation in temperature can be defined as that depth at which the time of maximum temperature coincides with the time of minimum temperature. As the times of maxima and minima for the various depths lie on straight lines which are not parallel, they will intersect if produced, the point of intersection being the depth at which the maximum and minimum temperatures occur at the same time. As the time of minimum is variable, the depth of intersection of the lines of the times of maxima and minima will also vary. The depths of intersection for January and July have been obtained by producing the lines in Fig. 4. In July, the depth of the point of intersection is 108 cm. In January, the depth of the point of intersection is 142 cm. The depth of 108 cm. in July agrees well with that calculated from the observations in desert sand, the variation at a depth of 96·9 cm. in the desert sand being calculated as one-thousandth of a degree centigrade for a surface heating amplitude of 36° C.

From this reasoning, however, the paradoxical conclusion is reached that with a smaller amplitude of the surface wave in January there is an increase in the depth of the zone of daily variation as compared with July. The increased depth of the zone of daily variation during the winter is probably due to the increased length of the daily cooling period. The

magnitude of the variation in temperature in the increased zone of daily variation in the winter must be very small and could not be detected with the instruments used. Experimental proof of the existence of the increased zone of daily variation in the winter cannot yet be given.

The Influence of Cloud on Soil Temperatures.

The influence of cloud on the temperature of the soil during the day is to reduce the temperature owing to the interception of radiation from the sun. At night the reverse effect takes place as the cloud prevents the radiation of heat from the earth's surface. A typical cloud effect at night is shown in Fig. 5 *a*, *b* and *c*. These are the records obtained of a cloud effect at the surface, 5 cm. and 10 cm. depths on the night of July 23–24, 1924.

The sky was clear until 3 a.m. and cooling by radiation took place normally. At this time the cloud appeared above the fallow plot and prevented radiation from the soil surface. The result has been a rise in the soil surface temperature. The effect is still noticeable at 5 cm. but not at 10 cm.

The soil temperature conditions at 3 a.m. were: surface, 22·3° C.; 5 cm. 25·8° C.; 10 cm. 33·0° C.

It will be seen that heat was passing from a depth of 10 cm. to the surface at the time of appearance of the cloud. As radiation ceased at the surface on the appearance of the cloud, the heat passing upwards from the lower depths increased the temperature at the surface and 5 cm. depths. The normal effect of a cloud at night is, therefore, to reduce radiation. The direction of heat flow near the surface being upwards at this period, a rise in surface soil temperature takes place. As the surface thermometer responds immediately to the presence of cloud, it forms an excellent method of recording the state of the sky at night.

The Effect of Rain on Soil Temperatures.

The effect of irrigation on soil temperatures has been recorded previously (5). The effect of irrigation on the surface temperatures depends on the temperature of the irrigating water. The effects below the surface are dependent on the displacement downwards of water already in the soil by the irrigation water. The effect of an irrigation on the soil temperatures below the surface depends on the temperature conditions of the soil at the time of irrigation. The effect of rain on soil temperatures is of a similar type to that produced by irrigation.

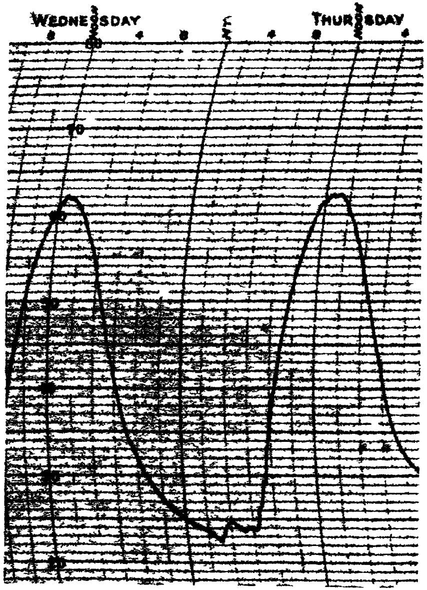


Fig 5 a Cloud effect at surface

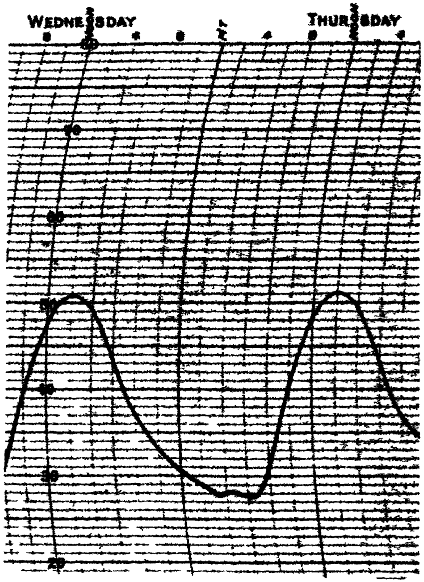


Fig 5 b Cloud effect at 5 cm

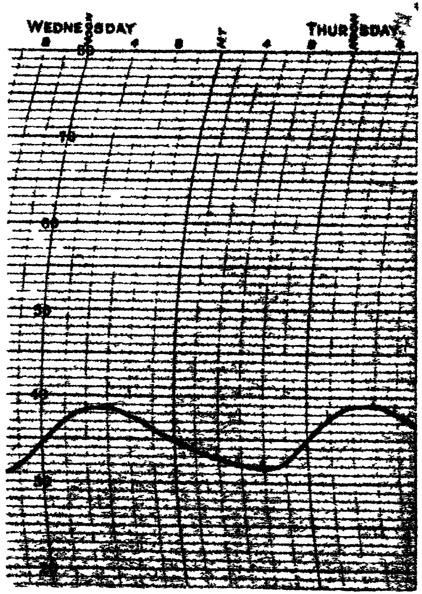


Fig 5 c Cloud effect at 10 cm

Rain is of rare occurrence at Giza, but one record has been obtained which shows its effect on the soil temperatures. Rain occurred on May 10, 1923. The morning was free from cloud, a maximum temperature of 55° C. being noted at the surface. The sky became cloudy at 1.30 p.m. and a little rain fell at 2 p.m. After this shower the clouds disappeared and the surface soil temperature rose again. A heavy thunderstorm broke at 4 p.m. The soil temperatures at the commencement of the storm are shown in Table IX.

Table IX. *Soil temperatures at* 4 *p.m. on May* 10, 1923.

Depth (cm.)	°C.	Depth (cm.)	°C.
Surface	39·0	15	28·8
5	30·5	20	25·0
10	30·0	30	24 5

In addition to rain, a considerable amount of hail also fell. The temperature at the surface fell almost immediately to 3·8° C., increasing to 16° C. after the storm. A small initial rise in temperature followed by a rapid fall was noted at a depth of 5 cm. At 10 cm. the temperature continued to be the same for a period of about 20 min. after the commencement of the storm; subsequently a rapid fall took place. At 15 cm. a small but sharp rise in temperature was noted, followed by a fall. At 20 cm. and 30 cm. rises in temperature occurred which were maintained. The characteristic variations in temperature noted under irrigation also occur with rain. The effect of rain on the soil temperatures below the surface is dependent on the displacement of water already in the soil by the rain. If this displaced water is of a higher temperature than the soil layer through which it passes, a rise in soil temperature will be observed. If the displaced water is of a lower temperature than the soil layer through which it passes, then a fall in soil temperature will be observed. The effect of rain on soil temperatures below the surface is determined mainly by the soil temperature conditions at the commencement of the rain. The final effect will depend on the depth of penetration of the rain and upon its temperature.

SOIL ISOTHERMS.

The soil isotherms were drawn in order that a value for the heating of the soil during weekly periods of the summer fallow in Egypt might be obtained. The method of obtaining the soil isotherms is illustrated in Figs. 6 and 7, isotherms being drawn for the average day in January and July. The area of an isotherm in centimetre-hours gives the heating value of the day.

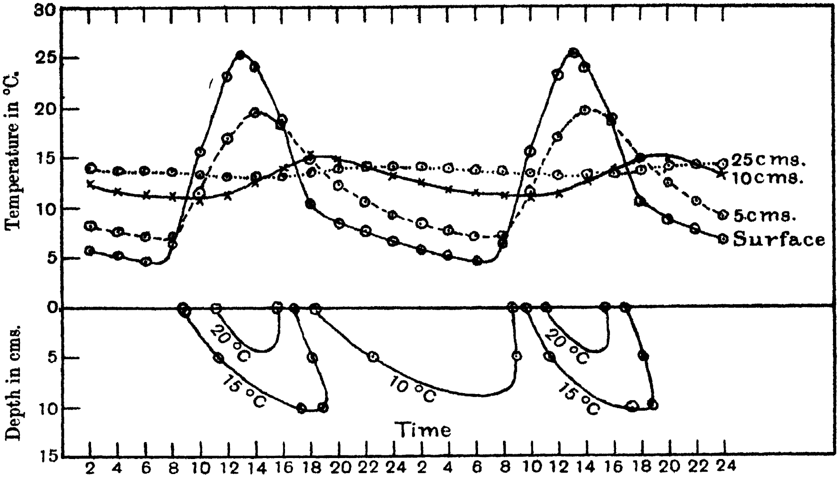


Fig. 6. Soil temperatures and isotherms for average day in January.

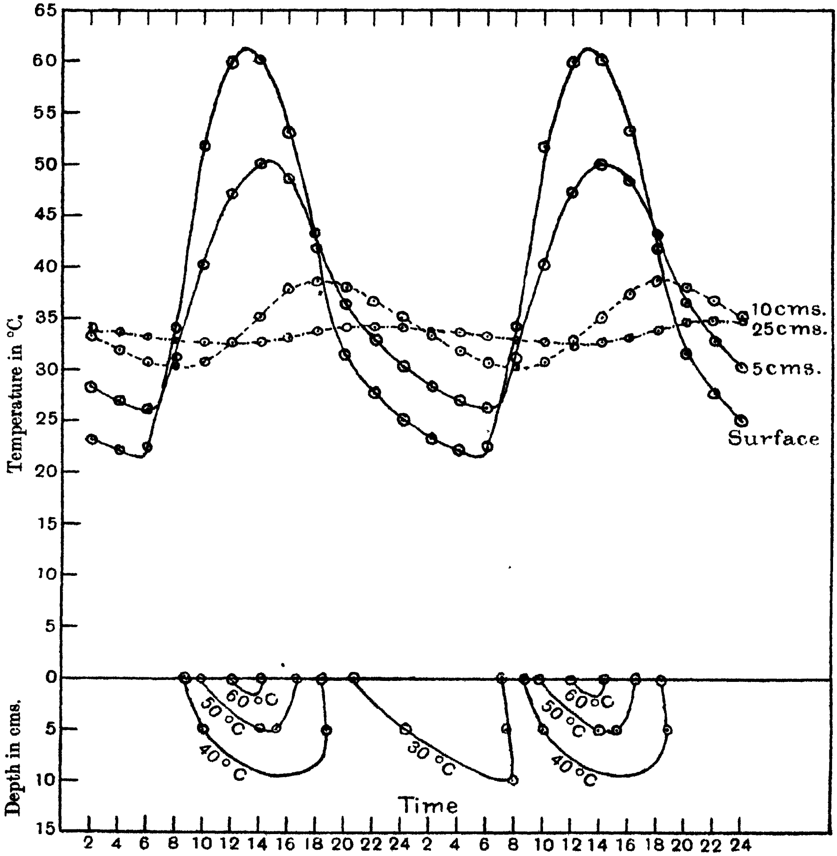


Fig. 7. Soil temperatures and isotherms for average day in July.

The method of dealing with soil temperatures through the soil isotherms was found to be of considerable value in the investigation of the summer fallow period in Egypt. Russell (6) states that a temporary rise in bacterial numbers, when suitable conditions are re-established, follows the heating of the soil to 45° C. and a permanent rise in bacterial numbers follows the heating of the soil to 50° C. The 50° C. soil isotherm has been drawn for the average day during weekly periods from June to August. The weekly sums of the areas of these isotherms are shown in Table X.

Table X. *Weekly totals of areas of 50° C. isotherms (cm.-hr.).*

May 29–June 4	103	Fallow under basin and perennial irrigation commences.
June 5–June 11	118	
June 12–June 18	131	
June 19–June 25	152	End of fallow under perennial irrigation since 1900.
Total......	504	
June 26–July 2	161	
July 3–July 9	169	
July 10–July 16	172	
July 17–July 23	170	
July 24–July 30	175	
Total......	847	
July 31–Aug. 6	167	
Aug. 7-Aug. 13	153	Fallow formerly ended under basin irrigation and under perennial irrigation before 1900.
Total......	320	

The summer fallow in Egypt has been an enforced characteristic of the agriculture from the earliest times. Flinders Petrie (7) gives the date of the commencement of this fallow as the beginning of April and the end of the fallow as August 23 in ancient Egypt. The wheat crop is usually harvested by the beginning of June so that the fallow can be regarded as starting from this date. Under basin and perennial irrigation prior to 1900, the fallow lasted until about August 10. Since 1900, the method of using the stored water has been altered and the summer fallow now lasts only from June 1 to about June 25 and has ended as early as June 15. The value of the heating effect of a fallow from June 1 to August 10 is represented by the sum of the areas of the daily 50° C. isotherm. This value is approximately 1650 centimetre-hours. The corresponding value of the heating effect of a summer fallow lasting from June 1 to June 25 is approximately 500 centimetre-hours. The curtailment of the length of the summer fallow period as the result of the alteration in the method of using the stored water has reduced the heating value of the fallow by

more than 66 per cent. The bearing of this reduction in the length of the summer fallow on the decline in soil fertility in Egypt since 1900 as evidenced by the fall in the yield of cotton has been dealt with previously (8).

The soil isotherms afford a method of assessing the agricultural value of the day from the point of view of the heating effect.

Soil-Temperature as a Biological Factor.

The soil temperatures dealt with in this paper are those in fallow land. They differ considerably from the soil temperatures under crops. An account of the soil temperatures under cotton has already been given (1). The soil temperatures during a fallow are of importance in two connections: (*a*) their effect on the micro-organic population of the soil, and (*b*) the temperature conditions of a seed-bed and the root temperatures in the initial stages of plant development. It is not proposed to deal with the effects in detail but only to indicate the general conditions.

(*a*) *Soil Temperatures and the Micro-Organic Population of the Soil.*

Keen and Russell (4) suggest that the soil organisms are living under conditions similar to those of an incubator kept at 20° C. during the summer months in England. This conclusion is based on the records of the 6 in. thermometer which is probably below the zone in which the maximum density of the soil population occurs. The density of the micro-organic population of the soil is probably greatest between the 2nd and 4th in. The temperature conditions of this layer will, therefore, be those of the greatest importance. The extremes of temperature will be of more importance than the mean temperature in determining the effect of temperature. Fig. 8 shows the mean monthly maximum and minimum for each month of the year at depths of 2 in. and 4 in. in Egypt.

A temperature of 37° C. is usually regarded as the optimum temperature for bacterial activity, a modification in the population taking place when the soil is heated above 40° C. From Fig. 8 and from the soil isotherms, it will be seen that in a fallow soil between May and September, the maximum temperature at 5 cm. is well above the optimum temperature and for a considerable period each day is above that temperature which produces the modification in the micro-organic population known as partial sterilisation. At 10 cm., however, the maximum temperature is near the optimum. From the soil isotherms it appears that the micro-organic population in the top 8 cm. of the soil in Egypt will be submitted to temperatures that will lead to partial sterilisation. Prescott (9) has

shown that partial sterilisation does take place in Egypt during the summer fallow in the areas under basin irrigation. Below a depth of 8 cm. it is unlikely that temperature becomes the factor limiting bacterial activity. In Egypt, the presence or absence of natural vegetation closely follows the maximum temperature curve for 5 cm. In general, while the maximum temperature in the fallow at 5 cm. is in excess of 42° C. there is no natural vegetation; below a maximum temperature at

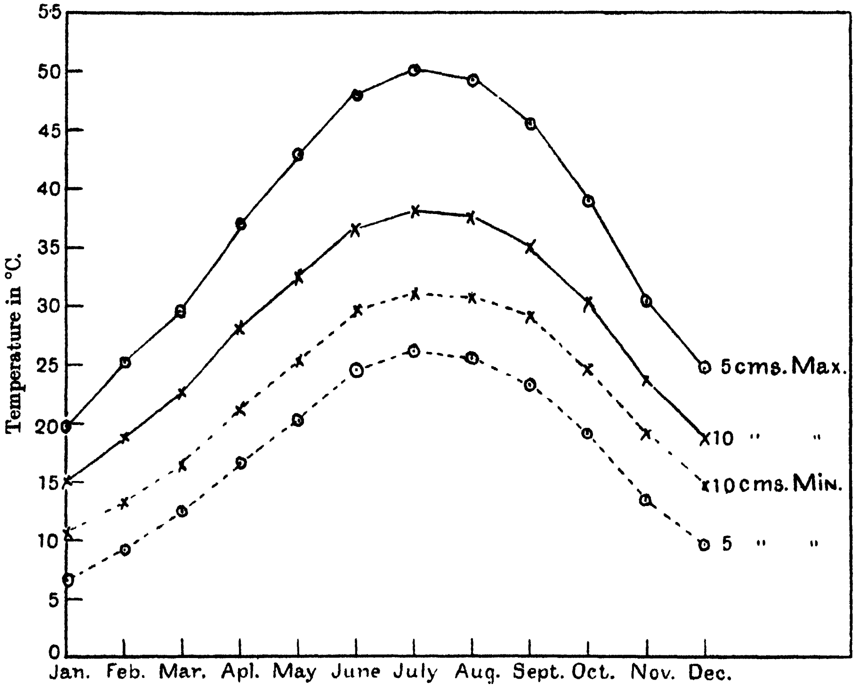


Fig. 8. Mean monthly maxima and minima at 5 cm. and 10 cm.

5 cm. of 42° C. a natural vegetation is present. This was particularly noticeable in connection with the fallow plot in which the soil temperatures were being recorded. It seems probable that bacterial activity may vary in the same manner.

During March and April, and also during October and November, the soil temperatures at 5 cm. and 10 cm. are all within the zone that may be regarded as suitable for micro-organisms. During December, January and February, although the maximum temperature in the 5 cm.–10 cm. layer may be regarded as suitable, the minimum temperature is probably too low. It seems that the minimum temperature in the winter and the maximum temperature in the summer will be the factors limiting bio-

logical activity at these seasons. The micro-organic population of the soil in Egypt undergoes considerable daily and annual variations in temperature, the daily range amounting to 25° C. and the annual range to 45° C.

(*b*) *Temperature of Seed-Beds and Plant Roots.*

It has been shown in connection with the soil temperatures under cotton that, at the time of germination of the seed, the temperatures of the seed-bed are very similar to those in a bare fallow. If we assume that the normal depth of sowing is about 5 cm., the temperatures at 5 cm. in the fallow will indicate fairly accurately the temperature of the seed-bed at germination. Table XI shows the indicated temperatures of the seed-beds for the various crops grown in Egypt.

Table XI. *Temperature of seed-beds of various crops.*

Crop	Date of sowing	Temperature of seed-bed Max. °C.	Temperature of seed-bed Min. °C.
Cotton	End of February	27	10
Maize	Beginning of July	50	26
Wheat	Early November	30	13
Berseem	Early October	39	19

The seed-bed is subject to considerable daily variation in temperature, and, in some cases, the maximum is much higher than the temperature normally considered an optimum for germination. This is particularly so in the case of maize. In the initial stages of growth, before the shading effect of the crop has developed, the roots will also be subjected to a considerable daily range in temperature. The daily range of root temperature has been studied in detail in connection with the cotton plant and has formed the subject of a previous paper.

Bailey and Trought (10) have pointed out a possible connection between the growth of the cotton plant and the soil temperatures at 20 cm. depth. They state that at 20 cm. depth there are a considerable number of absorbing roots, and that the rise and fall in the rate of elongation of the plant coincides with the rise and fall in the temperature curve at this depth. They attribute this to the increase in water absorption with rise in temperature.

High soil temperatures may have a harmful effect on roots, as has been indicated by Howard (11). He records that, during the high temperatures of June and July in the Quetta Valley in India, unless the soil is kept cool by a deep vegetable mulch, apricot seedlings invariably

withered. He further states that the trees are planted close together so that they soon produce a shading effect on the soil. In other words, as in the case of cotton, the trees control to a large extent the soil temperature conditions to which their roots are subjected.

Temperature as a Factor in Geological Weathering.

The shattering of rocks in desert zones is usually attributed to sudden changes of temperature due to the difference between day and night temperatures. The following may be quoted as typical of the statements on this subject: "Here (in the desert zones) the temperature by day is extremely high, while after sunset owing to the clear sky radiation is strong and *the fall of temperature is very sudden.* In consequence of this the rocks are cracked and shattered to a great extent (12)."

The supposition that there is a sudden fall in temperature of the rocks at sunset is not borne out by either the soil temperature records at Giza or by the desert sand temperatures recorded by Williams in Wadi Digla. It does not appear to have been realised that the surface soil starts cooling soon after 1 p.m. and that between 1 p.m. and sunset the cooling takes place at the maximum rate. The surface soil temperature records show that between sunset and sunrise the rate of cooling is at a minimum for the 24-hr. period, and that there is no sudden fall in temperature at sunset. As the rate of change of temperature is at a minimum between sunset and sunrise, the temperature strains set up in the surface layers of the rock will also be at a minimum during this period. That the shattering of rocks is due to a sudden fall in temperature at sunset does not appear to be supported by observation.

The soil temperature records afford information as to the reason for the cracking of the rocks and the time of day that the cracking may be expected to take place. As the flaking of rocks is a surface phenomenon it will take place at the time when the surface layers are subject to the greatest strain due to thermal changes. The strain will be greatest when the rate of change of the difference in temperature between the surface and underlying layers is at a maximum. The differences in temperature at two-hour intervals throughout the day between the surface and 5 cm. depths for July 22 and January 17 are shown in Fig. 9.

During July, the greatest rate of change of the difference in temperature is taking place between 6 a.m. and 8 a.m., and in January between 8 a.m. and 10 a.m. The minimum rate of change of the difference in temperature in both July and January takes place between sunset and sunrise. Associated with the greatest rate of change of the difference in

temperature will be the greatest strain in the surface layers of the material. It would be expected, therefore, that the cracking of the rock would take place on the rising portion of the daily temperature wave and probably soon after sunrise. Although records of the cracking of rocks exist, there appears to be no record of the time at which the cracking was observed.

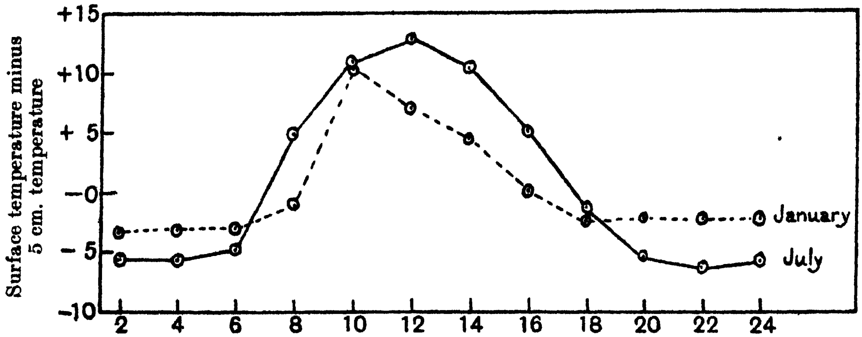


Fig. 9. Differences in temperature at two-hourly intervals between surface and 5 cm. depths, January and July.

Summary and Conclusions.

1. The soil temperatures in Egypt at a number of depths have been recorded by means of continuous recording thermometers. In general, the records show that the amplitude of the temperature wave at the surface of the soil is considerably greater than the air temperature wave. There is, however, a considerable damping of the wave with depth, no daily variation in temperature being observed at a depth of 100 cm.

2. No definite relation between the air and soil temperatures could be traced. The maximum air temperature was recorded in May and the maximum soil temperature in July.

3. The amplitude of the temperature wave decreases with increase in depth. The decrease in amplitude of the soil temperature wave is not regular owing to variations in the physical properties of the soil layers. Between any two depths, the ratio of the amplitudes of the temperature waves is constant throughout the year. The amplitude of the soil temperature wave bears no relation to the amplitude of the air temperature wave.

4. The time of maximum temperature at the soil surface is constant throughout the year at 1 p.m. The times of maximum temperature at depths below the surface lag behind the time of surface maximum, but they are constant throughout the year. When plotted against depth, the times of maximum at the various soil depths lie on a straight line.

5. The time of minimum temperature of the surface soil is variable and occurs just before sunrise. At depths below the surface, the times of minimum lag behind that of the surface though the time lag in the minimum is not so great as the time lag in the maximum. When plotted against depth, the times of minimum lie on a straight line.

6. Three types of alteration of the phase of the temperature wave are recorded: (*a*) an alteration with season, (*b*) an alteration with depth, and (*c*) an alteration dependent upon the direction of flow of heat in the soil below the zone of daily variation in temperature. As a result of the alteration in phase of the temperature wave, the duration of heating and cooling varies with depth. The greater the depth, the greater the period of heating and the shorter the period of cooling.

7. Owing to the seasonal and depth alterations in the phase of the temperature wave, the depth of the zone of daily variation in temperature is variable, being greatest in winter and least in summer.

8. The presence of cloud at night has been shown to result in the raising of the temperature of the surface soil due to the prevention of radiation and the conduction of heat from the hot layers of soil below the surface.

9. The valuation of the summer fallow by means of the soil isotherms is discussed.

10. It has been shown that the soil layer in which the micro-organic population is most dense, in which the germination of the seed takes place, and in which the roots of young plants are situated, is subject to both large daily and seasonal variations in temperature.

11. It has been shown that the supposed sudden fall in temperature of the surface of rocks at sunset does not occur. It is indicated that rock shattering as a result of temperature changes probably takes place soon after sunrise.

REFERENCES.

(1) Taylor, E. McK. (1927). Soil Temperatures under Cotton in Egypt. *Journ. Agric. Sci.* **17**, 489–501.

(2) Taylor, E. McK. and Williams, C. B. (1924). A Comparison of Sand and Soil Temperatures in Egypt. *Bull. No.* **40**, *Min. of Agric., Cairo.*

(3) Rambaut, A. A. (1900). Underground Temperatures at Oxford in the Year 1899. *Phil. Trans.* Series A, **195**, 255.

(4) Keen, B. A. and Russell, E. J. (1921). The Factors Determining Soil Temperature. *Journ. Agric. Sci.* **11**, 211–239.

(5) Taylor, E. McK. (1924). The Effect of Irrigation upon Soil Temperatures. *Bull. No.* **53**, *Min. of Agric., Cairo.*

(6) Russell, E. J. (1927). Soil Conditions and Plant Growth. P. 342. 5th ed. London.

(7) Flinders Petrie, W. M. (1923). *Social Life in Ancient Egypt.* Pp. 129, 130. London.

(8) Taylor, E. McK. and Burns, A. C. (*a*) (1922). The Basis of Egyptian Agriculture and its Relation to the Decline in the Average Yield per feddan of Cotton. *Bull. No.* **25**, *Min. of Agric., Cairo*; (*b*) (1924). Soil Temperatures during the Sharaqi Period and their Agricultural Significance. *Bull.* **31**, *Min. of Agric., Cairo.*

(8) (*c*) Taylor, E. McK. The Effect of the Sharaqi Period upon the Yield of Cotton in Egypt, *Bull. No.* **57**, *Min. of Agric., Cairo.*

(9) Prescott, J. A. (1919). *Journ. Agric. Sci.* **9**, 233.

(10) Bailey, M. A. and Trought, T. (1927). Growth, Bud-Shedding, and Flower Production in Egyptian Cotton. *Bull. No.* **65**, *Min. of Agric., Cairo.* Pp. 13, 14.

(11) Howard, A. (1924). *Crop Production in India.* P. 171. Oxford Univ. Press.

(12) Rastall, R. H. (1916). *Agricultural Geology.* P. 49. Cambridge.

(*Received October 2nd*, 1927.)

LOSS INVOLVED BY IGNITING SOIL FRACTIONS DURING THE MECHANICAL ANALYSIS OF SOILS.

By F. J. MARTIN, M.A., Ph.D., F.I.C.
(*Lands and Forests Department, Sierra Leone.*)

(With One Text-figure.)

In the report (1) on the Mechanical Analysis of Soils issued by a sub-committee of the Agricultural Educational Committee in a recent number of this *Journal* the following recommendation is made:

> We do not propose any change in the present practice of expressing the fractions on an ignited weight basis. While it is undoubtedly true that ignition drives off water chemically combined with clay and certain hydrated minerals, our experience is that this error is less variable than that occasioned by using the oven-dry weight (100–105° C.). In the latter case organic matter is not destroyed and the distribution of this constituent among the fractions is very variable, particularly in this country, where soils rich in organic matter are common. In such cases the figure for the clay fraction would be unduly weighted.

The committee refer specifically to English soils, that is to soils of a temperate country, and it is of interest to study the losses on ignition of soils of tropical countries to see how far methods designed for temperate climates are suitable for adoption in the tropics.

The weathering processes in tropical countries are somewhat different from those of temperate zones, and where the rainfall is heavy and the temperature high, lateritic soils are formed. The more soluble constituents, sodium, potassium, calcium, etc., are removed while much of the silica is also removed, alumina remaining as the chief constituent of such soils; the iron also remains in the soil. With such soils the loss on ignition is often very high and an examination of these losses and their origin has been made, while chemical analyses of the separate fractions were carried out to see if the losses on ignition could be correlated with the composition of the soil.

The clay fraction was first examined. The loss on ignition was determined, then the organic matter, and the "combined water" was taken as the loss on ignition minus the organic matter, it having been determined that there was no mineral carbonate present in these fractions. The organic matter was determined by dry combustion and the weight of the organic matter obtained by multiplying the organic carbon by 100/55.

The results are given in Table I, and in addition to soil clays, clays of other origins are given for comparison. Attention is directed to the relation between the "combined water" and the silica/alumina ratio.

Table I. *Losses on igniting the clay fraction.*

Origin of sample	Loss on ignition	Org. Mat.	Comb. water	Silica/Alu. ratio
Bentonite, Canada	8·9	(A)	8·9	6·22
Black clay soil, Gezira, Sudan ...	15·2	N.D.	—	3·90
Brown alluvial soil, Kassala, Sudan	14·2	N.D.	—	3·77
Red "Goz" soil, Kordofan, Sudan	13·1	N.D.	—	2·85
Ball clay, England	10·4	0	10·4	2·66
China clay, England	12·4	0	12·4	2·11
Swamp soil, Mabang, Sierra Leone	24·1	10·7	13·4	1·89
Lateritic sandy loam, Sierra Leone	19·8	2·7	17·1	1·74
Black grit, Konno, Sierra Leone ...	31·1	16·3	14·8	1·66
Gravel soil, Konno, Sierra Leone ...	31·0	6·0	25·8	1·50
Gravel soil, Moiamba, Sierra Leone	28·2	7·0	21·2	1·24
Gravel soil, Freetown, Sierra Leone	40·2	15·5	24·7	1·10
Bauxite, Sierra Leone (B)	25·3	(A)	25·3	0·32
Laterite crust (B)	26·6	0	26·6	0·30

N.D. means not determined; (B) means not clay fraction;
(A) not determined but negligible.

Unfortunately the organic matter was not determined in the Sudan samples but these soils generally have a low organic matter content; the organic matter in the clay fraction would not be very high, probably from 2 to 5 per cent. It will be seen that the loss on ignition in the Sudan samples varies from 13·1 to 15·2 per cent., while in Sierra Leone soils it varies from 19·8 to 40·2 per cent. The loss is partly due to organic matter and partly to combined water; in the case of the Sierra Leone soils the greater part is due to combined water while probably the same is true of the Sudan soils although the actual figures were not obtained.

Variation of combined water with silica/alumina ratio. Examination of Table I shows that there is a very close connection between the silica/alumina ratio and the combined water; the higher the silica/alumina ratio the less is the amount of combined water. This is shown in Fig. 1, where the amount of combined water is plotted against the silica/alumina ratio and, excepting for one erratic result, the points fall closely about a mean curve. An exact relationship is hardly to be expected since the amount of iron in soil clay generally varies from about 5 to 15 per cent. (as Fe_2O_3) and therefore affects the amount of silica and alumina present although it does not necessarily affect the silica/alumina ratio. Further, the degree of hydration of the various clay constituents present may possibly vary to some extent without any alteration in the proportions of silica and alumina.

An example of the effect of the presence of iron is given below, these two particular clays being selected from sub-soil samples because there was little or no humus present to serve as a cause of further complication.

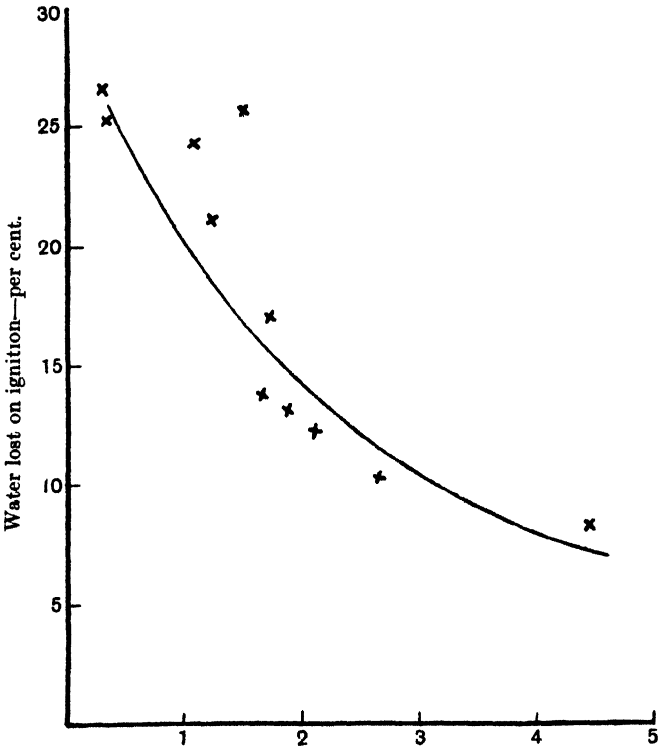


Figure 1. Silica/Alumina ratio.

Table II.

	SiO_2	Al_2O_3	Fe_2O_3	Comb. water	Silica/Alu. ratio
Grey clay, Sierra Leone	41·4	38·1	0·2	18·5	1·84
Yellow clay, Sierra Leone	33·2	31·1	19·2	14·5	1·81

The figures given in Table I show that where soils of a lateritic nature (those with a low silica/alumina ratio) are concerned the loss of combined water in the clay fraction is high. Further examinations were made to see if the lateritic material were uniformly distributed throughout the soil and if the losses on ignition of the coarser fractions are of the same order as in the clay.

Four types of tropical soils were selected, two of a lateritic nature

from a hot wet climate (Sierra Leone), and for comparison two, not of a lateritic nature, from a hot dry climate (Sudan). These are described below:

(*a*) *Red laterite soils, Sierra Leone.* These are of a rich red colour which often changes to a reddish yellow with depth. They contain a large proportion of stones and gravel and this fraction is mainly composed of lateritic concretions which are highly ferruginous. It contains very few quartz particles in any of the fractions.

(*b*) *Brown lateritic sandy soil, Sierra Leone.* This soil is usually brown or yellowish brown in colour; it is generally supposed to be of alluvial origin and contains a high proportion of fine and coarse sand, the sand fractions being composed mainly of quartz particles.

(*c*) *"Badob" or black cotton soil* from Gezira, Sudan (2). This soil is a heavy dark brown clay soil of aeolian origin. It is characterised by a high proportion of clay and a low one of silt. The stones and gravel consist chiefly of black nodules composed largely of calcium carbonate, and it usually contains a high proportion of salts soluble in water.

(*d*) *"Goz" soils*, Kordofan, Sudan (2). These red sandy soils consist mainly of "sand" and the "sand" fractions are chiefly composed of particles of quartz. Stones and gravel are absent and the clay varies from 5 to 50 per cent., but is usually less than 20 per cent. They vary colour from reddish brown to bright red.

Table III. *Losses on igniting soil fractions. Per cent. of oven-dry soil.*

	Stones & gravel	Coarse sand	Fine sand	Silt	Clay
Laterite, Sierra Leone ...	10·3	16·4	22·3	27·3	40·1
Lateritic sand, Sierra Leone	—	0·9	2·8	15·9	24·1
Badob, Sudan	36·3	34·7	1·6	6·4	15·2
"Goz," Sudan	—	0·7	0·8	8·7	13·1

In Table III are given the losses on ignition of the separate soil fractions of all four soils, and these are of such wide variation both in the same soil and in similar fractions of different soils that a further examination was made both of the chemical composition of each soil fraction and of the substances lost during ignition. These analyses are given below in Tables IV–VIII. It is pointed out that these soils were not treated with acid prior to separation of the fractions, and any losses due to the evolution of carbon dioxide would not normally be found if the Agricultural Education Association method were used. Only one sample however, the Badob soil, contained any calcium carbonate.

Stones and gravel. These include particles larger than 2 mm. in diameter and figures are only available in two cases, the "badob" soil from the Sudan and the laterite from Sierra Leone.

Table IV. *Stones and gravel.*

Description of soil	SiO_2	Al_2O_3	Fe_2O_3	CaO	Loss on ignition H_2O	Organic matter	CO_2
Laterite, Sierra Leone	12·8	30·0	46·4	—	9·6	0·7	—
Badob, Sudan ...	7·7	5·8	1·2	46·4	—	—	36·2

It will be noted that whereas the badob soil lost 36·3 per cent. on ignition due entirely to loss of CO_2 and nothing due to water, the laterite lost 9·6 per cent. due to water.

Coarse sand. The comparison in these cases is not strictly accurate since the Sudan fractions were from 0·2 to 2 mm. in diameter, while the Sierra Leone fractions were from 0·2 to 1 mm. in diameter. The fractions are however sufficiently similar to allow of some comparison.

Table V. *Coarse sand.*

Description of soil	SiO_2	Al_2O_3	Fe_2O_3	CaO	Loss on ignition H_2O	Organic matter	CO_2
Laterite, Sierra Leone ...	26·3	34·7	20·0	2·5	12·5	3·9	—
Lateritic sand, Sierra Leone	87·1	6·9	4·0	trace	—	0·9	—
Badob, Sudan	10·4	6·5	1·3	44·9	—	—	34·7
"Goz," Sudan	98·0	0·3	1·1	0·5	—	0·7	—

Here the differences due to loss on ignition are distinct. In only one case is there any appreciable loss on ignition due to water, and this is in the case of the laterite where it is over 12 per cent. The coarse sand fraction from the lateritic sandy soil lost little water and, like that of the Goz soil, was composed mainly of quartz particles.

Fine sand. These fractions consist of particles varying in size from 0·02 mm to 0·2 mm.

Table VI. *Fine sand.*

Description of soil	SiO_2	Al_2O_3	Fe_2O_3	CaO	Loss on ignition H_2O	Organic matter	CO_2
Laterite, Sierra Leone ...	29·3	32·1	13·2	2·0	15·2	7·1	—
Lateritic sand, Sierra Leone	75·6	12·4	7·7	trace	—	2·8	—
Badob, Sudan	75·6	6·3	8·0	4·5	—	1·0	0·6
"Goz," Sudan	94·5	1·4	1·1	0·6	—	0·8	—

The losses in the fine sand fractions are similar to those of the coarse sand, except that the loss due to water in the case of the laterite has increased to over 15 per cent. Of the other soils the chief constituent was quartz and there was little loss in these soils due to water.

Silt. This fraction includes particles varying from 0·002 to 0·02 mm. in size.

Table VII. *Silt.*

Description of soil	SiO_2	Al_2O_3	Fe_2O_3	CaO	Loss on ignition: H_2O	Loss on ignition: Organic matter	Loss on ignition: CaO
Laterite, Sierra Leone ...	28·9	29·3	11·2	1·6	14·2	13·1	—
Lateritic sand, Sierra Leone	42·0	31·1	9·4	0·6	10·0	5·9	—
Badob, Sudan	53·7	12·8	10·3	6·3	6·4		1·5
"Goz," Sudan	63·5	11·1	0·9	2·2	8·7		—

It is unfortunate that the separate figures for water and organic matter were not obtained for the Sudan samples. The figures show variations in losses from 7·9 to 27·3 per cent. The losses are partly due to humus and partly to water, and it should be noted that both lateritic soils lost a high proportion of water.

Clay. This fraction includes all particles less than 0·002 mm. in diameter.

Table VIII. *Clay.*

Description of soil	SiO_2	Al_2O_3	Fe_2O_3	CaO	Loss on ignition: H_2O	Loss on ignition: Organic matter	Loss on ignition: CaO
Laterite, Sierra Leone ...	18·7	28·2	9·6	trace	24·7	15·5	—
Lateritic sand, Sierra Leone	31·7	31·0	10·8	trace	20·2	3·9	—
Badob, Sudan	46·7	20·2	12·4	1·1	15·2		—
"Goz," Sudan	42·1	25·1	14·4	0·8	13·1		—

The loss on ignition in the clay fractions varies from 13·1 to 40·2 per cent. and the variation is partly due to organic matter but chiefly to water. Although the amount of organic matter is not given for the Sudan soils, the organic matter in the Sudan soils is usually very low, generally less than 1·0 per cent. and the humus in the clay fraction is presumably low. Of the losses on ignition up to 24·7 per cent. is due to water and up to 15·5 per cent. due to organic matter.

It will be seen that, using the Sudan method of analysis, there are three causes of losses on ignition, namely carbon dioxide, water and organic matter. If preliminary acid treatment is given the loss due to CO_2 should be eliminated, although in some cases (3) the use of large quantities of acid to effect solution of all the calcium carbonate may cause appreciable losses in the clay. An interesting point, very clearly marked in all the analyses, is that soil fractions with a high silica content lose but little water on ignition whereas soil fractions having a high

alumina content, or rather a comparatively high proportion of alumina to silica, lose a great deal of water when ignited. The essential characteristic of lateritic soils is a high proportion of alumina and a low proportion of silica and these soils are prevalent wherever the temperature is high and the rainfall heavy. It will be seen from Tables IV–VIII that the lateritic material in soils is not evenly distributed throughout the soil, fractions being in some cases chiefly confined to the clay as in the lateritic sandy soil described above or spread throughout the whole of the fractions as in the case of the laterite soil. Where the lateritic material is spread through the soil the losses on ignition are high in all the fractions, but where this material is confined to any fraction or fractions, *e.g.* the clay and possibly the silt, these fractions are the only ones that lose much water on ignition.

Losses on igniting laterite. The losses on igniting laterite are well known to be very high and this is presumably due to the presence of gibbsite ($Al_2O_3 . 3H_2O$) which may be present sometimes in a minutely crystalline condition but more usually in the colloidal form—kliachite or sporogelite (4). H. and F. J. Warth (5) found that the amount of water in Indian laterites varied from 7·7 to 28·1, and Lacroix (6) found up to 32·0 per cent. in French Guinea, while Koert (7) found 27·9 per cent. of water in laterite concretions at the Amani Experimental Station, Tanganyika.

When some fractions are lateritic and some are not, the losses of water on ignition in the same soil may vary from 1 per cent. in a non-lateritic fraction to 20 per cent. in the lateritic fraction as in the case of the lateritic sandy soil instanced above.

Our present practice in Sierra Leone therefore is to express our results on an oven-dry basis and to remember that the clay fraction is weighted with the humus. The organic matter on each first foot soil sample is determined separately and this gives a very good idea of the humus present in the clay fraction (all the humus—about half the organic matter—being considered as removed with the clay). Determinations of humus on 73 samples of soil from various parts of Sierra Leone showed that the humus varied between 1·0 and 2·0 per cent. in the majority of these soils, while in the Sudan, where a similar procedure is followed, the humus is generally less than 1·0 per cent.

SUMMARY.

1. Examinations have been made of the losses involved by igniting fractions of tropical soils.

2. It has been found that these losses are partly due to organic matter and partly to combined water; the greater part of the loss is due to water.

3. In the clay fraction there is a correlation between the amount of combined water and the silica/alumina ratio; the greater the ratio the less the combined water. This is affected by the proportion of iron present.

4. Lateritic soils lose more water on ignition than other soils but the lateritic material in soils is not necessarily evenly distributed throughout the fractions; those fractions containing the highest proportions of lateritic material lose the most water.

ACKNOWLEDGMENTS.

The writer wishes to express his thanks to Dr A. F. Joseph for permission to make use of results obtained by the Wellcome Tropical Research Laboratories, Mr H. C. Doyne who carried out many of the analyses, and Dr B. A. Keen for his kindly criticisms.

REFERENCES.

(1) A Sub-Committee of the Agricultural Education Association "The mechanical analysis of Soils" (1926). *Journ. Agr. Sci.* **16**, 123.

(2) JOSEPH, A. F. (1924). "The composition of some Sudan Soils." *Journ. Agr. Sci.* **14**, 490.

(3) JOSEPH, A. F. and MARTIN, F. J. (1921). "The determination of Clay in Heavy Soils." *Journ. Agr. Sci.* **11**, 293.

(4) THORPE, E. (1922). *Dictionary of Applied Chemistry*, **4**, 37.

(5) WARTH, H. and F. J. (1903). "The composition of Indian Laterite." *Geol. Mag.* N.S. Decade 4, **10**, 154.

(6) LACROIX, A. (1913). "Les latérites de la Guinée et les produits d'altération qui leur sont associés." *Nouv. Arch. Mus. Paris*, **5**, 255.

(7) KOERT, W. (1904). *Geologisch-agronomische Untersuchung der Umgegend von Amani in Ostusambara; Berichte über Land- und Forstwirtschaft in Deutsch-Ostafrika*, **2**, 143. Heidelberg.

(*Received October 4th*, 1927.)

THE REACTION, EXCHANGEABLE CALCIUM, AND "LIME REQUIREMENT" OF CERTAIN SCOTTISH SOILS.

By W. G. OGG and W. T. DOW.

Soils Department, Edinburgh and East of Scotland College of Agriculture.

In the present state of our knowledge there is no single method by which we can estimate the so-called "lime requirement" of soils, but by the application of several tests—usually in conjunction with field experiments—the lime needs of soils for particular crops can be ascertained with a fair degree of certainty. Valuable assistance in such work has been obtained in recent years from the application of methods of determining hydrogen-ion concentration, exchangeable bases, degree of saturation, etc., and when sufficient data of this kind have accumulated in various centres it may be possible to estimate "lime requirement" with much greater accuracy than has hitherto been possible.

Extensive data on pH values are already available in many countries and a beginning has been made with the estimation of exchangeable bases. In Scotland, the absence of free calcium carbonate, the high "lime requirement" by the Hutchinson and Maclennan method, and the acidity of certain fertile soils have been pointed out by Hendrick and Ogg ((1) and (2)), and determinations of exchangeable bases have been carried out by Smith (3) and Hendrick and Newlands (4). No extensive investigation, however, bearing on the lime status of Scottish soils has hitherto been published, and it was therefore thought desirable to bring together some of the results accumulated in the course of advisory and survey work by the writers during the past few years.

In addition to serving the more immediate practical needs of information on "lime requirement," data of this kind give information on the problems of soil development and soil type. The study of pH, exchangeable calcium and "lime requirement" of soils, by throwing light on the amount of leaching which has occurred, will help to determine the position of particular soils in a broad climatic scheme of grouping and may enable generalisations to be made as to the principles on which soils of wide areas require to be treated. To take the particular case of "lime requirement," the accumulation of such data should help not only to

determine the lime requirement of particular soils for particular crops but to determine the general liming policy of whole districts.

It is, of course, recognised that deductions must be made with caution. Soil acidity may be due to different causes, and reaction, exchangeable bases and "lime requirement" may be profoundly influenced by the amount and kind of the organic matter and by other factors such as texture, drainage, and the influence of man. The subject matter of the paper is arranged under the following headings:

Methods.
The Soils examined.
Range of *p*H found in Surface Layer.
Exchangeable Calcium.
"Lime Requirement."
Comparison of Surface and Sub-Surface Layers.
Comparison of Cultivated and Uncultivated Soils.
Climatic Relationships.
Geological Relationships.
Vegetation Relationships.

METHODS.

Reaction. The *p*H was determined in the majority of the soils by the electrometric method, using Biilmann's quinhydrone electrode. Ten grams air-dry soil passing the 3 mm. sieve, 20 c.c. CO_2-free distilled water and a few decigrams of quinhydrone were shaken for one minute and the determination carried out as described by Biilmann (5). In a large number of cases the results obtained in this way were compared with results by the colorimetric method (Gillespie's drop ratio method (6), using soil and water in ratio 1 : 2 as before), and close agreement was found for soils with a *p*H below 7. In a few cases a difference of *p*H of 0·2 was obtained and above *p*H 7 larger differences. For soils with a *p*H of less than 7 the electrometric, and above 7 the colorimetric figures were taken.

Exchangeable calcium. The exchangeable calcium was determined by treating 50 gm. of air-dry soil passing the 3 mm. sieve with normal ammonium chloride solution. The soil was first stirred up with about 200 c.c. of the warm solution and allowed to stand overnight. The supernatant liquid was decanted through a filter and the soil stirred up with a further quantity of about 100 c.c. cold solution. This in turn was decanted after having been stirred thoroughly and allowed to settle, and the process was repeated until one litre of filtrate was collected. A second

litre was then collected separately in the same way. The bulk of the filtrate was reduced to about half by evaporation, and aluminium and iron were precipitated as hydroxides. Calcium was precipitated as oxalate and determined volumetrically. The second litre was treated in the same way and any calcium obtained was subtracted from the amount in the first litre. The results have been expressed as percentages of CaO present in the air-dry soil.

"*Lime requirement.*" The "lime requirement" was determined by the Hutchinson and Maclennan method (7). Twenty grams air-dry soil passing the 3 mm. sieve and 300 c.c. $N/50$ calcium bicarbonate were shaken for three hours and titrated with 0·2 N HCl using methyl orange as indicator. The results have been expressed as gm. $CaCO_3$ per 100 gm. air-dry soil.

THE SOILS EXAMINED.

The soils examined may be divided into three groups, the first representing a general study of a wide area, the second a more intensive study of a small district, and the third an intensive study of a single farm.

A. Samples over a Wide Area.

This group consisted of about 750 samples obtained in the course of advisory work and drawn from more than 250 farms of which 63 were in East Lothian, 43 in Perthshire, 39 in Fifeshire, 26 in Midlothian, 18 in Forfarshire, 15 in West Lothian, 14 in Aberdeenshire, 11 in Berwickshire, 9 in Peeblesshire, 8 in Roxburghshire, and the remainder in Orkney, Inverness-shire, Kincardineshire, Kinross-shire, Clackmannanshire, Stirlingshire, Selkirkshire, Ayrshire, and Renfrewshire. They may, therefore, be regarded as relating especially to the Lothians and East Coast.

Since many of the soils were examined at the request of farmers who were not altogether satisfied with the condition of their soils, it seems probable that the cultivated soils examined may be slightly more acid than the average for these districts, although it might be argued on the other hand that the farmer who is sufficiently interested in his soils to have them examined may be depended upon to keep them in at least average condition.

In the case of about 130 of these soils, the examination was extended to one or more of the subsurface layers and in some cases to the complete profile.

B. Samples from Six Square Miles near East Saltoun in East Lothian.

In connection with a soil survey carried out in this district an examination of the soils was made with regard to acidity. A large number of colorimetric tests by means of brom-thymol blue were made in the field, and in addition surface and subsurface layers of over 100 samples were examined in the laboratory. Most of this locality is under cultivation, but there are a few woods in which the soils appear never to have been disturbed. This district includes an area of alkaline soils and was chosen in order to investigate more fully the occurrence of such soils, which are by no means common in Scotland.

C. Samples from the College Experimental Farm, Boghall, Midlothian.

A very detailed examination has been made of the soils of this farm, which lies at the foot of the Pentland Hills and consists of 230 acres arable and 370 acres hill land, the latter being used for sheep grazing. Part of the hill constituted the original farm and was cultivated over 100 years ago before the present arable land had been drained. There is, therefore, material on the farm for the comparison of cultivated, long-unploughed, and virgin land. About 170 surface samples were examined and the sub-surface layers were also tested in many places.

The soils in each of these groups have been considered according to the state of cultivation as follows:

(1) *Cultivated soils.* Most of these are cropped in rotations which vary from district to district but which usually include oats, turnips, hay, pasture grass, and in many cases barley, potatoes and wheat.

(2) *Long-unploughed soils.* These bear traces of cultivation but have been uncultivated for 50 and in some cases well over 100 years. Some of them represent the fringe of cultivation on the hill sides which has been allowed to go back into permanent grass for economic reasons; a few are the grounds of mansion houses and have been left in grass for amenity reasons.

(3) *Woodland soils.* Most of the samples examined were chosen as virgin profiles for comparison with the adjoining cultivated land. In the cases examined the woods were coniferous.

(4) *Hill and heath land.* This is covered in some cases with heather and in others with grasses. Land of this kind occupies a large area in Scotland and is used principally for sheep grazing. Some of the hill and

heath land was covered with trees until comparatively recent times and may be similar in nature to the woodland soils. Grazing, however, may have brought about considerable changes. For example, grass in many places seems to have replaced heather and the peaty surface has in consequence been altered.

An attempt has been made to consider the results of these investigations in relation to geology, vegetation, state of cultivation and rainfall. When further soil survey work has been carried out it will probably be found that such data can most usefully be linked up with soil varieties. At the present stage this has been found possible only on a limited area of Boghall hill.

Range of *p*H found in Surface Layer.

The *p*H of the surface layers of the soils examined shows the range indicated in Table I. The samples from cultivated and long-unploughed land were taken to a depth of nine inches. Those from land which appeared never to have been disturbed consisted of the top layer. In most cases this was peaty, but in some of the hill or heath soils it was largely mineral.

Table I. *Range of p*H *values.*

Location & state of cultivation	Number of soils in various reaction *p*H groups: 3·5–3·99	4–4·49	4·5–4·99	5·0–5·49	5·5–5·99	6·0–6·49	6·5–6·99	7·0–7·49	7·5 & over	Total
General (chiefly S.E. Scotland)										
Cultivated	—	8	37	128	201	156	75	43	33	681
Long-unploughed	—	1	8	8	—	—	1	—	—	18
Woodland	6	2	2	—	—	—	—	—	—	10
Hill or heath	7	8	15	6	2	1	—	—	—	39
East Saltoun District										
Cultivated	—	—	—	1	8	21	16	26	25	97
Woodland	2	4	3	3	—	—	—	—	—	12
Boghall Experimental Farm										
Cultivated	—	1	4	8	19	34	2	—	—	68
Long-unploughed	—	7	9	22	24	4	1	—	—	67
Woodland	—	1	—	—	—	—	—	—	—	1
Hill or heath	1	16	12	4	2	—	—	—	—	35

A. Samples over a Wide Area (chiefly South-east of Scotland).

The figures show that of the 681 cultivated soils examined 485 (71 per cent.) had a *p*H of between 5 and 6·5 and 201 (30 per cent.) had a *p*H of between 5·5 and 6. The number of alkaline soils 76 (11 per cent.) is probably much above the average for the area. The majority of these

alkaline soils were found within limited districts in Fifeshire and the Lothians, and a large proportion of the total number of samples came from these counties. Soils with a *p*H of less than 5 might be classed as extremely acid and 45 (7 per cent.) come within this category.

Most of the long-unploughed soils show a *p*H of between 4·5 and 5·5, and it is probable that high acidity has contributed largely to the discontinuance of their cultivation, but it is also probable that the acidity has increased since cultivation ceased.

The woodland soils in all the cases examined had a litter and peaty covering several inches thick and it was this that was examined. In the majority of cases this had a *p*H of less than 4, and in every case it was below 5. The hill and heath soils were also found to be very acid, 30 samples out of 39 (77 per cent.) showing a *p*H of less than 5, and only one having a *p*H of over 6.

The number of soils examined is too small to enable very definite conclusions to be drawn, but the figures indicate that the *p*H of the surface layer of the majority of the cultivated Scottish soils examined lies between 5 and 6·5, and that in the case of long-unploughed, woodland, and hill or heath soils the surface layer ranges between *p*H 3·5 and 5·5—the most acid being the woodland soils.

According to Russell (8) the *p*H of British soils ranges from 4·0 to 8·3 but normal fertile soils have a *p*H of 7 to 8. The figures found for normal soils in Scotland are much below this and workers in several other countries have also found low values—Glinka (9) in a study of the acidity of soils in the neighbourhood of Leningrad found a *p*H value of 4·5 for forest podsol soils, and *p*H 5·5 to 6·2 for the corresponding arable soils. For lowland moor soils he found the value 5·5 to 6. Brenner (10) in Finland found that of 815 cultivated soils examined by him 81 per cent. had a *p*H value between 5 and 6·5 and 42 per cent. between 5·5 and 6. Less than 2 per cent. had a *p*H of over 7. Christensen (11) found that of 5000 mineral soils examined in Denmark 74 per cent. had a *p*H between 6 and 7, and Niklas and Vogel (12) from an examination of 2225 cultivated soils in Bavaria found that (measured in a KCl extract) more than half had a *p*H of less than 6·2. According to Arrhenius (13) 50 per cent. of 5000 Swedish soils examined had a *p*H of between 6 and 7 and 26 per cent. a *p*H of 7 or over.

The following table given by Arrhenius compares the range of soil reaction for several countries, and the values for South-Eastern Scotland have been added.

It will be observed that the figures quoted by Arrhenius for Denmark

and Finland show slight variation from those quoted above and are probably taken from different sources.

Table II. *The soil reaction of different countries.*

(The figures give the percentages of soils in the various reaction groups.)

*p*H ... Country	4·0– 4·4	4·5– 4·9	5·0– 5·4	5·5– 5·9	6·0– 6·4	6·5– 6·9	7·0– 7·4	7·5– 7·9	8·0– 8·4	8·5– 8·9	> 9·0
Denmark (5000)	—	1	3	12	46	21	14	2	—	—	—
Finland (500)	1	8	23	38	21	8	1	—	—	—	—
Sweden (5000)	1	2	5	10	25	31	24	2	·03	—	—
Egypt (56)	—	—	—	—	—	—	14	48	22	—	16
Japan (27)	—	19	19	15	23	19	5	—	—	—	—
Java (73)	—	—	—	—	—	14	57	26	3	—	—
S.E. Scotland (681)	1	6	19	29	23	11	6	5	—	—	—

The figures for Scotland agree fairly closely with the results found in several other countries, especially Finland, and are what might be expected in a cool moist climate.

B. Samples from East Saltoun district.

The soils from this small area show a much higher *p*H than the average found for the wider area. As has already been pointed out, however, this district was selected in order to study the occurrence of alkaline soils. Of the cultivated soils no fewer than 53 per cent. had a *p*H of over 7, and only 9 per cent. had a *p*H of less than 6. Under timber, the surface layer in every case was strongly acid, but less acid than the surface layer of the woodland soils in the wider area. In this small district there is a fairly wide range of *p*H, but considerable uniformity of reaction is observable if the acid and alkaline portions are considered separately, for it was found that the alkaline soils occurred more or less together in one part of the area. The boundary between the acid and alkaline portions was ascertained fairly satisfactorily by means of field tests with brom-thymol blue, and the distribution of these soils points to the fact that their alkalinity is natural and not due to liming. This is further discussed when dealing with geological relationships.

C. Samples from Boghall Experimental Farm.

The soils from Boghall show a wide range of reaction for such a small area, but the farm includes both arable and hill land and geologically is very varied. The cultivated soils show a comparatively small range—nearly all falling between *p*H 5 and 6·5 and the majority between 6 and 6·5. An intensive study of a single field showed the *p*H to range from 5·76 to 6·66 for 32 samples. This field was not particularly uniform in

appearance and has probably a greater range of reaction than an average field for this part of the country.

An investigation by Němec and Gracanin (14) of the reaction of the soils of the College Experimental Farm at Prague showed a range of *p*H of 5·8 to 7·5 in soils under cultivation and 6·1 to 7·5 in the grasslands. No soils of extreme acidity were found by them.

In the long unploughed land at Boghall two entirely different classes occur—(*a*) an area of naturally well-drained hill land representing an old farm, and (*b*) a small area of peaty ill-drained land lying within the present arable section. The *p*H of the former varied from 4·5 to 6 and of the latter from 4 to 5.

Most of the undisturbed class of soils on the hill had a *p*H ranging from just under 4 to about 5 but a number of undisturbed soils with a higher *p*H were also found—due no doubt partly to the percolation of water containing a considerable amount of bases in solution and partly to surface creep of the soils on the slopes. This applies also to certain of the long-unploughed soils on the hill.

Exchangeable Calcium.

The exchangeable calcium, which promises to give useful information regarding soils, was determined in 60 soils widely distributed over the south-east of Scotland. The range of results and the average *p*H value corresponding to each group are shown in Table III.

Table III. *Range of exchangeable calcium values.*
(*Soils from various parts of South-east of Scotland.*)

Number of soils in various exchangeable calcium groups, and average *p*H.

State of Cultivation	% CaO	Exchangeable calcium groups (expressed as % CaO) 0–0·049	0·05–0·099	0·1–0·149	0·15–0·199	0·2–0·249	0·25–0·299	0·3–0·349	0·35–0·399	0·4–0·449	0·45 & over	Total
Cultivated	No.	—	2	4	3	3	3	7	3	3	2	30
	*p*H	—	5·25	5·32	5·74	5·58	6·31	6·72	6·79	7·07	6·38	
Long unploughed	No.	4	2	2	1	—	—	—	—	—	—	9
	*p*H	4·72	5·03	5·27	5·29							
Woodland	No.	4	2	—	—	—	—	—	—	—	—	6
	*p*H	4·58	4·71									
Hill or Heath	No.	7	4	1	1	1	1	—	—	—	—	15
	*p*H	4·54	4·77	6·14	5·32	5·25	5·62					

It will be seen from the above results that the exchangeable calcium in the cultivated is much higher than in the uncultivated soils. All except two of the cultivated soils examined contained more than 0·1 per cent.,

expressed as CaO; whilst in most of the long uncultivated, woodland and hill or heath soils the surface layer (or subsurface where the surface was peat) contained less than 0·1 per cent. CaO. Nearly 25 per cent. of the cultivated soils fell within the group containing 0·3 to 0·35 per cent. CaO.

Smith (3) has determined the exchangeable bases of 20 Scottish soils, most of which came from the same area as the above, and good agreement has been found between the two sets of figures. Of the two uncultivated soils examined by Smith one was a wood soil and contained 0·04 per cent. CaO; the other was a hill soil and contained 0·11 per cent. CaO. The exchangeable calcium of his cultivated soils ranged from 0·12 per cent. to 0·55 per cent. CaO.

Figures by Robinson and Williams (15) for seven Welsh soils ranged from 0·05 per cent. to 0·43 per cent. CaO, and Kelley and Brown (16) found for a few American soils that the exchangeable calcium in neutral to slightly alkaline soils ranged from 0·12 to 0·92 per cent. CaO, and for a group of acid soils from 0·03 to 0·09 per cent. CaO.

Comparison of pH *and exchangeable calcium.* The results obtained show a fairly close relationship between *p*H and exchangeable calcium. Soils with less than 0·1 per cent. CaO had a *p*H of less than 5·5 whilst the soils with more than 0·3 per cent. CaO had a *p*H of over 6, but the figures of each class are too few to enable a satisfactory comparison to be made. Good agreement was found by Robinson and Williams for Welsh soils of about the same organic matter content and it seems probable that this agreement will be found to be general for soils of the same type.

"LIME REQUIREMENT."

Determinations of the "lime requirement" of over 300 soils were carried out and their distribution is shown in Table IV. Most of the samples examined were from cultivated soils widely distributed over the south-east of Scotland (Group A).

It will be seen from the table that the majority of these soils (63 per cent.) had a "lime requirement" ranging from 0·05 per cent. $CaCO_3$ to 0·25 per cent. $CaCO_3$. Of the cultivated soils examined 25 (7 per cent.) had no "lime requirement" and 25 (7 per cent.) had a "lime requirement" of less than 0·05 per cent. $CaCO_3$. On the other hand, 20 soils (6 per cent.) had a "lime requirement" of over 0·4 per cent. $CaCO_3$.

The long-unploughed and hill or heath soils examined showed much higher "lime requirement" than most of the cultivated soils—the figure ranging up to 0·9 per cent. $CaCO_3$ for one heath sample. These soils

frequently have an acid peaty surface layer which would help to account for the high "lime requirement."

Table IV. *Range of "lime requirement" values.*

(*Soils from various parts of South-east Scotland.*)

Number of soils in various "lime requirement" groups.
"Lime requirement" groups (expressed as % $CaCO_3$)

State of Cultivation	Below 0	0·01–0·049	0·05–0·09	0·1–0·149	0·15–0·199	0·2–0·249	0·25–0·299	0·3–0·349
Cultivated	25	25	58	62	48	47	23	21
Long-unploughed	—	—	—	—	—	—	1	3
Hill or Heath	—	—	—	—	—	1	1	—
Average pH	7·33	7·00	6·51	6·25	5·79	5·60	5·52	5·42

State of Cultivation	0·35–0·399	0·4–0·449	0·45–0·499	0·5–0·549	0·55–0·599	0·6–0·649	0·65 & over	Total
Cultivated	12	7	5	5	1	1	1	341
Long un-ploughed	2	3	3	1	2	1	2	18
Hill or Heath	—	—	—	2	2	1	1	8
Average pH	5·34	5·26	5·15	4·96	4·77	4·67	4·72	

Although many determinations by the Hutchinson and Maclennan method must have been carried out throughout the country, not many published results appear to be available for comparison. However, a few figures given by Saint (17), Robinson and Williams (15) and Hendrick and Ogg (2) indicate that "lime requirement" of 0·1 to 0·4 are quite usual.

It should be clearly understood that these figures are not to be regarded as representing the actual lime needs of the soils in question. The amount of lime required depends on a number of factors including the plant, the climate, and the nature of the surface and sub-surface layers, and figures obtained by laboratory tests of this kind must be interpreted with caution. It is useful, however, to know the amount of calcium carbonate which a soil will absorb under certain conditions from a bicarbonate solution, and this figure in conjunction with other laboratory tests and field experiments is useful in deciding the amount of lime it is necessary to apply.

As Crowther and Martin (18) have pointed out, it would be necessary, in order to secure comparable "lime requirements" for different soils, either to bring all the soils into equilibrium with a constant concentration of bicarbonate or to plot the "lime requirement" as a function of the equilibrium bicarbonate concentration and interpolate to some constant arbitrary value. This makes an appreciable difference only in cases of high "lime requirement", and no correction has been made in this paper.

Comparison of pH *and "lime requirement."* Table IV also gives a comparison of pH and "lime requirement" values, and although indi-

vidual samples frequently were exceptions to the rule the average pH of the groups falls steadily from 7·33 for soils with no "lime requirement" to 4·67–4·72 for soils with a "lime requirement" of over 0·6 per cent. $CaCO_3$. An examination of some of the exceptions showed that heavy soils had usually a higher "lime requirement" for the same pH than lighter soils. This was noted by Saint (17) and others, and is a natural consequence of the larger amount of colloidal material in a heavy soil. The agreement was usually very close for soils of similar texture and organic matter content on the same farm or from the same district, but on soils of different character the parallelism disappeared. For a number of Scottish soils Smith (3) found that the most acid soils as expressed by pH had the greatest "lime requirement" and the same result was obtained by Robinson and Williams (15) and Saint (17).

COMPARISON OF SURFACE AND SUB-SURFACE LAYERS.

Although the reaction of the sub-surface layers must have an important bearing on plant growth, and on the question of liming there is not much information on this subject available. Glinka (9) found that in the neighbourhood of Leningrad the surface soil had the highest acidity. Salisbury (19) determined pH, carbonate content and organic matter content of the surface layers of certain natural woodland soils and found a decrease in acidity (as measured by pH) with increasing depth. He found the top layer was poorest in bases and richest in organic matter—the organic matter decreasing rapidly with increasing depth. He called attention to the relation between organic content and real acidity, but pointed out that even under the same plant cover and on the same type of soil the pH values do not necessarily vary according to the fluctuations in organic content. He suggested that woodlands in general and probably all types of undisturbed plant communities in this country are tending to become progressively more acid.

Crowther (20) has studied the depth distribution of reaction in continuously manured soils compared with unmanured soils at Rothamsted and Woburn. In all cases examined there was a decrease in acidity with increasing depth. The unmanured soil at Woburn showed a marked fall in acidity at a depth of about nine inches and the manured soil showed a similar acidity curve but was more acid down to the full depth examined, viz. three feet. The Rothamsted unmanured plot showed a rather gradual change from pH 5·7 at the surface to pH 6·7 at 31½ inches, whilst the heavily manured plot ranged from pH 3·74 at the surface to pH 6·08 at 31½ in. Limed portions of the manured plots showed a reduction in

acidity throughout the whole depth. In the Rothamsted plots the reduction due to liming was fairly uniform throughout the profile but in the Woburn plots it was much more marked at the surface, and the whole profile was considerably less acid than the untreated profile. From these results it is clear that heavy manuring and liming may affect the reaction not only of the surface but also of the sub-surface layers to some depth.

A study has been made of the reactions of the sub-surface layers of the three groups of soils already described.

A. Samples from Various Parts of the South-east of Scotland.

The *p*H of the surface 9 in. and of the sub-surface 9–18 in. of 110 cultivated soils were determined. In 82 cases (75 per cent.) the sub-surface was less acid than the surface, in 8 (7 per cent.) there was no appreciable difference, and in 20 (18 per cent.) the sub-surface was more acid than the surface. The amount of difference is shown in Table V.

Table V. *Difference of p*H *between surface and sub-surface layers.* (*Cultivated soils from various parts of South-east of Scotland.*)

Amount of difference of *p*H	Number of soils with *p*H higher at 9–18 in. than at surface	Number of soils with *p*H lower at 9–18 in. than at surface
Less than 0·25	32	5
0·25–0·49	24	9
0·50–0·74	16	4
0·75–0·99	5	1
1·00 and over	5	1

Table VI. "*Lime requirement*" *of surface and sub-surface layers.*

Location	"Lime requirement" expressed as % $CaCO_3$ Surface	Sub-surface
Boghall, Midlothian	0·090	0·043
Boghall, „	0·119	0·106
Boghall, „	0·308	0·257
Boghall, „	0·288	0·241
Boghall Hill, „ (Uncultivated)	0·531	0·366
Boghall Hill, Midlothian (Uncultivated)	0·607	0·455
Boghall Hill, Midlothian (Uncultivated)	0·618	0·461
Dalkeith, Midlothian	0·139	0·103
Dalkeith, „	0·154	0·103
Bangour, West Lothian	0·115	0·143
Kirknewton, „	0·219	0·061
Kirknewton „	0·351	0·105
Lauder, Berwickshire	0·167	0·088
Largo, Fifeshire	0·544	0·353

Of 22 uncultivated soils (woodland and hill or heath) 16 (73 per cent.) had the immediate sub-surface less acid than the surface and 6 (27 per cent.) had this layer slightly more acid, but in all cases the succeeding layers were less acid than the surface and were progressively less acid with increasing depth. In many of these uncultivated soils, the surface layer consisted of litter and peaty material, and it was this layer that in some cases was less acid than the greyish leached mineral layer immediately beneath it. The reactions of several complete profiles are given later (Table X).

The "lime requirement" of 14 soils was also determined for the surface 9 in. and sub-surface 9–18 in. and in 13 cases the surface had a higher "lime requirement" than the sub-surface. The results are shown in Table VI.

An examination of three horizons of a cultivated and a heath soil gave the following results:

Table VII. *Exchangeable calcium and* pH *of a cultivated and a heath profile.*

	Cultivated soil		Heath soil	
Number of layer	Exchangeable calcium (as % CaO)	*p*H	Exchangeable calcium (as % CaO)	*p*H
1 (surface)	0·275	6·37	0·047	4·84
2	0·383	6·87	0·059	5·44
3	0·415	6·78	0·052	

It would appear from these figures that in both cases the surface layer had the lowest percentage of exchangeable calcium and the lowest *p*H. The second and third layers in these two soils showed little difference from each other.

B. Samples from East Saltoun District.

In this area of six square miles the *p*H of the surface layer was compared in a number of places with the *p*H of material at depths of 2 ft. and 4 ft. The differences found on the cultivated soils are shown in Table VIII.

It will be seen from the Table that by far the greater number of soils had a much lower *p*H at the surface than at depths of 2 ft. or 4 ft. Where samples were examined at both depths at the same spot, the *p*H as a rule was considerably higher at 4 ft. than at the shallower depth. Of 54 samples from cultivated land examined at 2 ft., 46 were alkaline, 6 acid and 2 neutral, and of 43 examined at 4 ft., 39 were alkaline, 2 acid and

2 neutral. It should be noted however, that from its geological relationships this area is probably much more alkaline than the average for Scotland.

Table VIII. *Difference of* pH *between material at surface and at depths of two feet and four feet.*

(*Cultivated soils in East Saltoun district.*)

Amount of difference of *p*H	Number of soils: *p*H higher at 2 ft.	*p*H lower at 2 ft.	*p*H higher at 4 ft.	*p*H lower at 4 ft.
Less than 0·25	5	7	4	4
0·25–0·49	6	1	5	2
0·50–0·74	7	—	3	—
0·75–0·99	8	1	8	—
1·00–1·24	8	—	6	—
1·25–1·49	9	—	3	—
1·50–1·74	6	—	4	—
1·75–1·99	2	—	2	—
2·00 and over	2	—	8	—

Woodland soils were examined in 11 places. It was found that, as in the wider area already discussed, the peaty layers in several cases were less acid than the first mineral layer. This has been noted by Salisbury (19) for woodland soils in calcareous districts. Apart from this, there was a rise in *p*H with increasing depth in every case. In some cases the rise was slow and even at 4 ft. the *p*H was only slightly higher than at the surface, but at depths of 6 or 7 ft. the *p*H had risen to over 7. In several places, natural sections enabled the reaction to be determined at depths of 20 to 30 ft., and in these the *p*H was approaching 8. The surface material (uncultivated) above this had a *p*H of just over 4, and cultivated land adjoining a *p*H of 5·5–7 in the surface 9 in.

C. *Samples from Boghall Experimental Farm.*

The reactions of the surface and sub-surface layers were determined both on the arable and the hill land and the differences are given in Table IX.

Table IX. *Difference of* pH *of surface and sub-surface layers: Boghall Experimental Farm.*

Amount of difference of *p*H	Number of soils: Cultivated: *p*H higher at 9–18 in.	Cultivated: *p*H lower at 9–18 in.	Long Unploughed: *p*H higher at 9–18 in.	Long Unploughed: *p*H lower at 9–18 in.	Hill or Heath: *p*H higher at sub-surface	Hill or Heath: *p*H lower at sub-surface
Less than 0·25	3	1	8	—	7	5
0·25–0·49	11	—	4	—	5	—
0·50–0·74	5	—	—	—	2	—
0·75–0·99	—	—	—	2	1	—
1·00–1·24	1	—	—	—	—	—

The figures show that as in the other areas examined the surface layer both of the cultivated and uncultivated land was usually decidedly more acid than the layer below. A considerable proportion (25 per cent.) of the hill or heath group, however, had the sub-surface layer more acid than the surface, and in two cases the sub-surface layer of the long unploughed soils was much more acid than the surface.

Table X. *Reaction of profiles.*

State of cultivation and location	Geological notes	*p*H of layers	Depth of last layer ft.
Cultivated:			
Boghall, Midlothian	Boulder Clay over Basalt	6·12, 6·61, 7·1, 7·5, 7·6	5
Boghall, Midlothian	Sand and Gravel over Basalt	5·77, 6·14, 6·31, 6·28	4
Arbroath, Forfarshire	Boulder Clay over Lower Old Red Sandstone	5·48, 6·64, 6·64, 6·57	4
Dunbar, E. Lothian	Boulder Clay over Carboniferous Limestone	7·37, 7·07, 7·94, 7·91	6
Aberlady, E. Lothian	Raised Beach	6·16, 7·47, 7·65	4
Boghall, Midlothian	Alluvial Flat	6·37, 6·87, 6·78, 6·93, 6·95	
Long unploughed:			
Boghall Hill, Midlothian	Thin Boulder Clay over Basalt	5·83, 5·98, 6·04	2
Boghall Hill, Midlothian	Thin Boulder Clay over Basalt	5·36, 5·57, 5·83	2
Lammermuirs, E. Lothian	Lower Silurian	4·91, 4·58, 5·12, 5·25, 5·25	3
Lammermuirs, E. Lothian	Boulder Clay over Lower Silurian	4·84, 5·44, 5·48, 6·07	4
Woodland:			
Countesswells, Aberdeenshire	Sandy Boulder Clay over Granite	3·52, 3·87, 4·03, 4·23	3
Quarry Wood, E. Lothian	Boulder Clay over Calciferous Sandstone	3·52, 3·95, 3·92, 4·17, 3·84, 4·68, 3·92, 4·25	4
Bolton Wood, E. Lothian	Boulder Clay over Calciferous Sandstone	3·94, 4·11, 4·40, 4·73	4
Inglesfield, E. Lothian	Boulder Clay over Calciferous Sandstone	4·11, 4·58, 4·65, 4·75, 5·55	4
Beugh Burn, E. Lothian	Boulder Clay over Calciferous Sandstone	4·42, 4·72, 4·75, 7·98	20
Moffat Wood, E. Lothian	Boulder Clay over Calciferous Sandstone	4·44, 3·92, 4·35, 4·89, 5·59	4
Bolton Wood, E. Lothian	Boulder Clay over Calciferous Sandstone	4·56, 4·10, 3·79, 3·92, 4·04, 3·97, 5·71, 7·30	7
Hill or Heath:			
Deeside, Aberdeenshire	Granite	3·59, 4·23, 5·03, 4·91, 5·10, 5·32	
Insch, Aberdeenshire	Diorite	5·29, 5·90, 6·02, 7·21	
Boghall, Midlothian	Boulder Clay over Basalt	4·33, 4·58, 4·98, 5·67, 6·74	
Insch, Aberdeenshire	Clay Slates	3·97, 3·77, 4·65, 5·05	

Reaction of Profiles.

In order to study the change in reaction to greater depths profile samples were taken and every distinct layer was tested. The results are given in Table X.

It will be seen from the figures that, although in general there was a steady decrease in acidity from the surface downwards the more acid second layer, already noted, was observed in a few cases and in one or two instances a fairly acid layer was encountered some distance from the surface. This has been noted by Wheeting (21) who has suggested it may be due to proportionally large amounts of iron and aluminium in that layer. A very acid condition persisted to a depth of 4 ft. or more in certain of the woodland soils and in several of the examples given above, the basal or C horizon was not reached.

From these sets of figures it would appear that as a rule the *p*H of the surface layer of soils in the south-east of Scotland is considerably lower than the *p*H of the sub-surface layers. The "lime requirement" is also greater and in the few cases examined the percentage of exchangeable calcium is less in the surface than in the sub-surface. Allowance should of course be made for the presence of different amounts of organic matter and for differences in texture, but the results indicate that there is a leaching of bases from the surface layers and a tendency to increasing acidity.

Comparison of Cultivated and Uncultivated soils.

In the sections of this paper dealing with range of *p*H exchangeable calcium and "lime requirement," the soils were arranged for comparison in groups of cultivated, long unploughed, woodland and hill or heath soils (Tables I, III and IV). These tables show that the cultivated soils are rather sharply marked off from the others by higher *p*H, higher amounts of exchangeable calcium and lower "lime requirement" in the surface layer.

As might be expected, the long unploughed soils approached nearest to the cultivated, and the woodland soils offered the greatest contrast. It has been found that, in general, the cultivated soils have a *p*H of 5 or over, a "lime requirement" of less than 0·4 per cent. $CaCO_3$ and an exchangeable calcium content of over 0·1 per cent. CaO, whilst the other groups have usually a *p*H of less than 5·5, a "lime requirement" of over 0·3 per cent. $CaCO_3$, and an exchangeable calcium content of less than 0·1 per cent. CaO.

In addition to this general comparison, a number of specific uncultivated soils were compared with adjoining cultivated soils. It is, of course, often difficult to decide whether soils were originally alike and in certain cases it is evident that the land which is now uncultivated was left because it was originally inferior to the land which was brought under cultivation. An endeavour has been made to avoid cases of this kind and land which appeared to have been at one time uniform was selected for the comparison.

The results are given below in Table XI. All the samples were from East Lothian and most of them are derived from Boulder Clay overlying the Calciferous Sandstone series of the Lower Carboniferous.

Table XI. *Comparison of the pH of uncultivated and cultivated soils: East Lothian area.*

Location	Uncultivated Surface *p*H	Uncultivated 2 ft. *p*H	Uncultivated 4 ft. *p*H	Adjoining cultivated Surface *p*H	Adjoining cultivated 2 ft. *p*H
Beugh Burn Wood	4·42	4·75	—	7·34	7·88
Bolton Muir Wood	4·33	3·84	4·25	6·80	7·56
Bolton Muir Wood	4·56	3·97	5·71	7·29	7·86
Upper Bolton Wood	4·73	5·05	—	6·26	7·74
Howden Wood	3·80	5·01	—	6·62	7·89
Lammermuirs (Kidlaw)	5·21	5·05	—	5·91	—
Lammermuirs ,,	4·91	5·25	—	5·32	—
Moffat Wood	4·44	4·89	5·59	5·67	—
Skimmers Hill Wood	4·58	5·36	—	6·20	6·87

The figures given in Table XI show that the uncultivated land was much lower in *p*H than the adjoining cultivated land which at one time was presumably the same. The exchangeable calcium was also determined in one case and showed the cultivated soil to have almost double the exchangeable calcium of the surface 9 in. of the adjoining uncultivated soil. (Cultivated 0·178 per cent. as CaO; Uncultivated 0·041 per cent. as CaO.)

Glinka (9) found, in the neighbourhood of Leningrad, that the *p*H value of podsol soils (uncultivated) was 4·5, whilst arable soil of the same class had a *p*H of 5·5 to 6·2. This pronounced difference must, therefore, probably be attributed to cultivation. Part of this effect is due to the mixing of the sub-surface layers, which are less acid, with the surface layer. In most cases the surface 9 in. of a cultivated soil would consist of a mixture of the peaty surface covering A_0, the surface leached mineral layer or layers A_1, A_2, etc., and often a part of horizon B, the zone of accumulation. The depth to which a very acid reaction extends—in many cases 4 ft.—makes this explanation inadequate however. The change

must no doubt be attributed partly to the heavy dressings of lime which it was customary to apply to land, especially at the time that it was being brought under cultivation, partly to the bases from some depth left near the surface by the more abundant root and other remains of crops, and partly to the action of earthworms and other soil organisms.

Certain portions of land along the coast have been much longer under cultivation than the rest of the country and have probably been agricultural land from the time of the Roman occupation or even earlier times. This land is, in general, less acid and more highly cultivated than much of the land which is known to have a shorter agricultural history. Records, obtained on three farms, of fields which have been under cultivation a much shorter time than the rest of the farm showed in every case a considerably lower *p*H on the more recently reclaimed land. Many of the long unploughed soils went out of cultivation at the time of the agricultural depression about 1870 when heavy liming became unremunerative.

Climatic Relationships.

The study of reaction and exchangeable bases throws light on soil development and classification, and according to the Russian School the broadest grouping of soils must be climatic. Climate determines very largely whether the soil bases will be washed out of the surface layers as in the podsols, or whether they will accumulate in the surface layers as in the tschernosem and solonetz groups. The composition of the parent material cannot be disregarded, however, unless under very extreme climatic conditions. The parent material in some cases may have a large reserve of bases or have these bases present in such a form that they are not readily exhausted by leaching, whilst in other cases the small quantity of bases originally present will quickly be washed out.

All the material examined in this investigation came from a region with an annual rainfall of 25 in. (625 mm.) or more, spread more or less uniformly over the year. The average number of hours of sunshine is less than 1300 per annum and the mean temperature is 38° F. (3·3° C.) in January and 58° F. (14·4° C.) in July. Although belonging to the dry area of Scotland the climate is more humid than the figures indicate and much more humid than many areas of the mainland of Europe with similar rainfall.

These conditions have given rise to leaching of bases from the surface layers and the development of acidity. This supports the conclusion arrived at from the study of the appearance and composition of the

profile (22) that the majority of Scottish soils belong to the podsol group. Three stages of podsol development seem to be represented, viz.:

(1) Brown earth of Ramann which occurs to a limited extent along the East Coast;

(2) Typical podsol containing a considerable admixture of mineral matter through the acid peaty layer;

(3) A variety found in parts of Sweden and elsewhere which has a surface layer of practically pure peat usually several inches thick.

Although in many cases, especially where the parent material is rich in bases, the grey leached layer in undisturbed profiles is not well developed, the tendency towards the typical podsol condition is seen in the high acidity of the surface layers. Glinka (9) found similar conditions in the podsol soils in the neighbourhood of Leningrad. The development of the podsol type in Scotland is due to the cool moist climate and the three sub-groups represent three degrees of leaching.

Most of the samples of arable soil were drawn from a region where the rainfall ranges from 30 to 35 in. per annum, but many of the hill soils had developed under a higher rainfall and the profiles of some of these are strongly acid to a depth of several feet. The samples of cultivated soils examined from hilly districts, such as the Lammermuirs (pH 4·5–6·0) or the Highlands of Perthshire (pH 5–5·5) were more acid than those from the drier districts around Arbroath (pH 5·5–7) and Dunbar (pH 5·5–over 7). The samples from areas of different rainfall and the same parent material are too few, however, to enable a satisfactory comparison to be made.

GEOLOGICAL RELATIONSHIPS.

On account of glaciation it is often difficult to decide what is the parent rock from which any particular soil is derived. The greater part of the cultivated land in Scotland is covered with glacial drift and to determine, even approximately, the origin of the matrix of this drift would involve a detailed mineralogical examination of the soils. Such examination has been carried out by Hendrick and Newlands (23) and is at present being carried out in this department. The results so far obtained indicate that, although boulders are frequently far-travelled, the matrix of the drift—at any rate where the drift is comparatively thin—is largely derived from the underlying rock.

In the present investigation, the soils were grouped according to the underlying stratigraphical formation or rock. Most of the arable samples occurred on glacial drift, but a few were soils derived *in situ* from the

rock. Too much stress cannot be laid on these figures, however, for the following reasons: (1) in a number of cases the drift may have little or no connection with the underlying rock; (2) the same stratigraphical formation may contain very different rock types and the same rock varies in composition from place to place; (3) the number of samples in every case is small (where very small the figures are omitted); (4) agricultural treatment such as liming and manuring may have altered the reaction to different extents on different formations. It is possible, however, to make a very general comparison and this is done in Table XII.

Table XII. *The* pH *of soils over various geological formations and rocks.*

	Number of soils in various *p*H Groups								
*p*H ... Geological formation or rock	4·0–4·49	4·5–4·99	5·0–5·49	5·5–5·99	6·0–6·49	6·5–6·99	7·0–7·49	7·5 & over	Total
Trachyte	—	—	1	8	4	2	3	—	18
Andesite	—	3	6	2	1	-	—	—	12
Basalt	—	3	9	7	16	11	8	6	60
Quartz Dolerite	—	—	1	7	1	—	—	—	9
Lower Silurian	1	7	12	14	6	2	—	—	42
Lower Old Red Sandstone	1	4	45	53	17	1	1	--	122
Upper Old Red Sandstone	—	2	4	20	14	11	7	2	60
Carboniferous (Calciferous Sandstone series)	2	13	18	20	12	15	2	—	82
Carboniferous (Carboniferous Limestone series)	—	—	1	2	4	9	16	9	41
Carboniferous (Coal Measures)	—	—	1	2	4	2	1	—	10
Alluvium	--	1	2	22	34	6	1	2 (raised beach)	68

The most outstanding relationship is in the case of the Carboniferous Limestone. The soils over this formation were obviously much less acid than over any other—two-thirds being alkaline. This may be understood when it is considered that glaciation has broken off much limestone from the outcrops with the result that the boulder clay on this formation is frequently full of limestone fragments. Where the boulder clay is at all stiff, it has helped to protect this limestone from leaching, and cultivation brings fresh pieces to the surface. Consequently such soils are frequently alkaline in reaction.

In the area at East Saltoun of which a detailed examination was made of the soil reaction, two series of the Lower Carboniferous are represented, viz.: the Calciferous Sandstone and the Carboniferous Limestone, and both are covered with glacial drift. It was found that in general the soils over the Carboniferous Limestone were alkaline whilst those over the Calciferous Sandstone were usually acid except near the boundary

with the Carboniferous Limestone area, where many alkaline samples occurred.

Apart from the tendency to alkalinity in the case of the soils over Carboniferous Limestone, the outstanding feature was the similarity in the reaction over the different rocks and formations. Of the samples examined, the soils approaching nearest to those over Carboniferous Limestone as regards reaction were those over basalt, of which about two-thirds had a *p*H over 6. The soils over trachyte, although not showing many alkaline examples, were not particularly acid—only one out of 18 falling below *p*H 5·5. The alluvial material also showed a tendency to moderate acidity, most of the samples falling between *p*H 5·5 and 6·5, and this was also the case with the soils over Upper Old Red Sandstone.

The more acid groups appeared to be over the Calciferous Sandstone series of the Lower Carboniferous, the Lower Old Red Sandstone, the Lower Silurian and the acid andesites. In these groups the majority of the samples examined showed a *p*H of less than 6.

Although the majority of the soils, irrespective of their stratigraphical formation, were of acid reaction except in the case of those over Carboniferous Limestone, the results showed a certain amount of agreement with the nature of the underlying rock. For instance, the limestone has given rise to the most basic soils and is followed by the basic volcanics. The Upper Old Red Sandstone in many places contains calcium carbonate which would account for the alkalinity of several samples over this formation. The same general tendencies were seen to a less extent on the uncultivated soils, but the number of samples was too small to allow conclusions to be drawn, and there appeared to be a fairly uniform acidity in the surface layers. The correlation might be clearer if more detailed information was available as to the petrographic character of the parent material.

Rainfall differences would affect the results, but the greater part of the area from which the cultivated soils were drawn has approximately the same amount and distribution of rainfall.

Differences in texture have a profound influence on soil reaction. These are frequently associated with the nature of the parent rock, *e.g.* shales would tend to give rise to heavy soils and certain sandstones to light porous soils. In the case of glacial drift, the method of deposition as well as the nature of the parent material must be taken into account. Glacial "sand and gravel" gives rise to lighter soils than "boulder clay" and the effect of the resulting freer drainage is sometimes seen in the reaction. The surface and very often the sub-surface layers to a consider-

able depth of light soils tend to be much more acid than the corresponding layers of heavy soils. This is no doubt due largely to the freer percolation of rain water and the consequent leaching out of bases.

The following examples of Boulder Clay and adjoining Sand and Gravel illustrate the tendency:

Table XIII. *Comparison of pH of profiles over "Sand and Gravel" and over "Boulder Clay."*

	pH Over "Sand and Gravel"					pH Over "Boulder Clay"				
Location	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Boghall experimental farm	5·77	6·14	6·31	6·28	—	6·12	6·61	7·1	7·5	7·6
Boghall experimental farm	5·91	6·14	6·35	—	—	6·40	6·36	6·74	7·3	—
Boghall Hill	4·60	4·58	4·89	4·96	5·05	4·33	4·58	4·98	5·67	6·74
Lammermuir	4·91	4·58	5·12	5·25	—	4·84	5·44	5·48	6·07	—

Vegetation Relationships.

Forest soils. Most of the forest samples examined had a litter and peaty covering with a pH of less than 5, and in some cases less than 4. The greyish mineral layer below this had about the same pH and a content of exchangeable calcium of less than 0·1 per cent. CaO. All the samples were from coniferous woods—mostly Scots Pine.

Hill or heath soils. The hill or heath soils were found to show considerable variation in vegetation. The higher rainfall frequently associated with hills brings about a more intensive leaching than is found on the neighbouring low land, and this tends to result in conditions of acidity and poverty in bases. This is counteracted in many places by the soil movement on slopes which exposes fresh unleached material on the surface, and by "flushing" with water, which, after passing through material rich in bases, comes to the surface and may give up some of its bases to the soil. This can have a marked effect in altering the herbage; for example, heather, when flushed with basic water, may be displaced by grass within a year, and shepherds are known to utilise this watering to increase or improve areas of grassland (24). The natural conditions on hill and heath land are also disturbed by grazing, burning of grass and heather and by former cultivation. There is thus a variety of conditions found on hill and heath land, and this is reflected in differences in reaction, content of exchangeable calcium and vegetation. The more extensive types of vegetation for Central Scotland were first mapped and

described by R. and W. G. Smith (25). Others, important for grazing, were added in a later survey ((26) and (27)).

The vegetation of the hill and heath soils examined has been grouped by Smith as follows: (1) *Calluna* and *Vaccinium* dominant; (2) *Ulex* and poor grass areas; (3) *Nardus* dominant and *Molinia*; (4) Rushy and sedgy areas; (5) Good grass areas. A short account of some of the hill soils of Boghall has already been published by one of us (28), and in the following table examples are given of several hill and heath soils carrying different vegetations. These vegetation groups have been found to coincide fairly closely with differences in soil profile.

Table XIV. *p*H *of soils in certain vegetation groups.*

	Number of soils in the various *p*H groups, *p*H of surface layer						
Vegetation	*p*H under 4	4–4·49	4·5–4·99	5·0–5·49	5·5–5·99	6·0–6·49	6·5–6·99
Calluna and Vaccinium	7	5	3	—	—	—	—
Ulex and poor grass	—	4	4	—	—	—	—
Nardus and Molinia	1	11	—	—	—	—	—
Rushes and sedges	—	3	11	8	18	4	1
Good grass	—	2	6	13	4	—	—

The *Calluna* and *Vaccinium* areas were found to have, as a rule, a black peaty surface layer over a greyish leached layer both of which had a low *p*H (3·5–4·5) and a low exchangeable calcium content (less than 0·1 per cent. CaO). Probably the roots of these plants reach down to the less acid sub-surface layers.

The *Ulex* areas were frequently associated with open texture and very free drainage, and this was accompanied by short herbage (*Festuca ovina*, etc.) and absence of black peaty covering. The *p*H and content of exchangeable calcium of these areas were also extremely low. The fact that *Ulex* was found also in "flush" areas of higher calcium content suggests that in the open textured dry and very acid areas its deep roots reach down to the less leached material at some depth.

The soil conditions of the *Nardus* areas appeared to approach closely those of the *Calluna* and *Vaccinium* areas. There was usually a black peaty surface layer (often very thin) and a greyish second layer, both of which had about the same reaction and content of exchangeable calcium as the *Calluna* and *Vaccinium* soils. The texture as a rule was fairly heavy and the drainage poor in winter. The underlying layers were much less acid and richer in exchangeable calcium than the surface, and as *Nardus* has long roots these penetrate the unfavourable surface layers and so reach the material below.

The rushy and sedgy areas examined were found to vary according to the source of the water. Where the wet condition was due to stagnant water or to water low in bases the soils were acid (pH 4–5) and low in exchangeable calcium, but in places where surface "flúshing" with water rich in bases had occurred the soils were not highly acid (pH 5–6), and under such conditions broad leaved grasses and clover were found associated with the rushes.

The good grass areas consisted chiefly of broad leaved grasses such as *Agrostis alba*, *Holcus*, *Cynosurus cristatus*, etc. These areas were not highly acid (pH 5–6) and contained more exchangeable calcium than any of the other types except the rushy areas flushed with water rich in bases. These good grass areas in some cases appeared to consist of down-wash from material derived from basic rocks and in other cases were flushed or irrigated by springs from basic areas. A marked difference can be observed between the portion of Boghall Hill derived from acid andesite and the portion from basalt. The former has a dark appearance at a distance and has a peaty surface layer with heather vegetation, whilst the basalt slopes are green from their grass covering. The nature of the rock appears to have had an influence on soil and vegetation.

The vegetation of cultivated soils in relation to reaction is much more difficult to follow on account of the numerous other factors involved. Some indication of the nature of the soils may be obtained, however, from the crops and crop rotations. The fact that oats, turnips and grass constitute the rotation on all the higher land in Scotland coincides with a high resistance of these crops to acid conditions which our results show to be more prevalent at higher altitudes. While the inclusion of potatoes, barley and wheat in a rotation is probably determined by climate, it is significant that wheat and the finer brewing (Goldthorpe) barleys are limited as a rule to coastal areas. Wheat and the finer barleys are grown up to 700 ft. altitude in East Lothian, and this coincides with the occurrence of considerable areas of the more basic soils. In few other parts of Scotland do these crops occur over 500 ft. Arrhenius (29) from a study of the crop rotations in relation to acidity on 30 farms in Sweden found that on the farms with the most acid soils the usual crops were timothy, oats and turnips. On farms with slightly less acid soils, rye was also found, and as the soils came nearer to neutrality clover and swedes were generally grown, and wheat and beet began to appear. On neutral and alkaline soils the rotation included sugar beet, wheat, barley, and lucerne. Similar results wère obtained by Hiltner in Bavaria. The bes wheat growing areas in Scotland—the Lothians and Fifeshire—are area

containing considerable stretches of land only slightly acid or even alkaline. It would appear, therefore, that the crops and rotations common in the south-east of Scotland are those which have been found best adapted to rather acid conditions.

The introduction of sugar beet and perhaps lucerne has raised the question of the suitability of Scottish soils in general to these crops. Most of the cases of beet failure investigated by the authors have been found on soils with a *p*H below 6, and a series of experiments laid down with and without lime on acid soils showed increased yields on the limed plots.

The authors have also examined the soils on which Cunningham (30) has carried out experiments on the growing of lucerne, and the results obtained are given in Table XV.

Table XV. *Field experiments on the growing of lucerne.*

*p*H groups	5–5·49	5·5–5·99	6·0–6·49	6·50–6·99	7·0 & over
Total No. of trials	4	7	7	7	9
Successful	—	2	6	6	8
Failure	4	4	—	—	—
Indefinite	—	1	1	1	1

These results indicate that in the cases of sugar beet and lucerne a satisfactory growth is not to be expected on soils with a *p*H below 6, and it is probable that even less acid soils than these would give a response to liming.

Of the 37 cultivated soils with a *p*H below 5 (Table I) one was reported by the farmer as a case of total failure of wheat, one as a case of failure of oats, several as soils on which barley would not grow, several as soils on which turnips suffered from finger and toe, and most of the remainder were cases of extremely poor pasture. The prevalence of such weeds as spurry, sorrel, and redshank was noted on most of these soils.

A case of barley failure on a very acid patch (*p*H 4·5–5) at Boghall Experimental Farm has been investigated by Williamson (31) who has applied dressings of several calcium compounds and has shown that calcium in various forms enables barley to be grown on this very acid soil. An investigation on the effect of liming on turnip yield has given rather indefinite results except in extremely acid soils.

The long unploughed soils on the borders of the Lammermuir Hills have a poor pasture consisting largely of fescues and *Nardus* without clover, and are in sharp contrast to the neighbouring cultivated area of alkaline soils around East Saltoun where the pasture is good and the clover extremely abundant.

Table XVI. *Effect of liming on turnip yield.*

Geological formation	pH	"Lime requirement" as % $CaCO_3$	Response to liming
Lower Carboniferous (Calciferous Sandstone)	4·75	0·478	Marked
Lower Silurian ...	5·24	0·335	Marked
Upper Old Red Sandstone ...	6·09	0·112	Marked
Lower Carboniferous (Calciferous Sandstone)	6·20	0·095	Indefinite
Lower Carboniferous (Coal Measures) ...	6·30	0·180	Marked
Lower Carboniferous (Calciferous Sandstone)	6·30	0·079	Slight

In contrast to the soils suffering from over-acidity a few cases have been found where crop failure can be attributed to alkaline conditions. Lime induced chlorosis (greyleaf) in oats is infrequent in Scotland, but four cases have been investigated on the Carboniferous Limestone in Fifeshire and Midlothian. The conditions which bring about this disease are not well understood, but it appears to be associated with alkaline conditions and in the cases studied the soils were all found to have a pH of over 7 and an exchangeable calcium content of over 0·4 per cent. CaO. In many places, however, oats are grown successfully on alkaline soils.

Summary.

1. Of a large number of cultivated soils examined, chiefly from the south-east of Scotland, the majority had a pH between 5 and 6·5, a "lime requirement" of 0·05 to 0·25 per cent. $CaCO_3$ and an exchangeable calcium content of 0·1 per cent. to 0·45 per cent. CaO.

2. A general agreement was observed between these three sets of figures although numerous exceptions occurred.

3. The reaction of a district of six square miles was studied in detail and of a single farm in still greater detail.

4. Long unploughed soils were found to have a low pH, a low content of exchangeable calcium and a high "lime requirement."

5. Woodland, hill and heath soils were characterised in their surface layers by an extremely low pH (below 5 as a rule), a low content of exchangeable calcium (usually less than 0·1 per cent. CaO) and a high "lime requirement."

6. The soils derived from Boulder Clay over Carboniferous Limestone were the most basic and were frequently alkaline; those over basic volcanic rocks, alluvium and Old Red Sandstone Conglomerate were as a rule less acid than the remainder. The relationship with geology might be clearer were more data available on the petrographic character of the rocks.

7. A considerable difference in reaction was observed between the surface and sub-surface layers of both cultivated and uncultivated soils—the sub-surface being less acid as a rule than the surface.

8. A comparison of cultivated and adjoining uncultivated land in several places showed that a great difference in reaction in the soil profile has been brought about by cultivation.

9. The results obtained point to leaching of the surface layers owing to the humid climate and support the view that Scottish soils in general belong to the podsol group.

10. Relationships have been observed between the above data and the natural vegetation. The usual crops and rotations are such as withstand acid conditions, and the introduction of sugar beet and lucerne will necessitate a return to the practice of liming.

REFERENCES.

(1) HENDRICK, J. and OGG, W. G. (1916). *Journ. Agr. Sci.* **7**, 458.
(2) —— (1920). *Agric. Educ. Assoc. Abstracts, Cambridge*, **8**.
(3) SMITH, A. M. (1925). *Journ. Agr. Sci.* **15**, 466.
(4) HENDRICK, J. and NEWLANDS, G. (1926). *Journ. Agr. Sci.* **16**, 584.
(5) BIILMANN, E. (1924). *Journ. Agr. Sci.* **14**, 232.
(6) GILLESPIE, L. J. (1920). *Soil Sci.* **9**, 115.
(7) HUTCHINSON, H. B. and MACLENNAN, K. (1915). *Soil Sci.* **7**, 73.
(8) RUSSELL, E. J. (1927). *Soil Conditions and Plant Growth.* 5th ed. London, 189.
(9) GLINKA, K. D. (1925). *Annals of the State Institute of Experimental Agronomy (Leningrad)*, **3**, 1.
(10) BRENNER, W. (192C). *Transactions of the Second Commission of the Internat. Soc. of Soil Science, Groningen*, A, 49.
(11) CHRISTENSEN, A. R. (1922). *Tidsskrift for Plant.* **28**, 733.
(12) NIKLAS, H. and VOGEL, F. (1925). *Proc. of the Internat. Soc. of Soil Sci.* I, **4**, 206.
(13) ARRHENIUS, O. (1926). *Actes de la IVème Conférence Internationale de Pédologie, Rome*, **2**, 502.
(14) NĚMEC, A. and GRACANIN, M. (1925). *Report of Ministry of Agric. of Czecho-Slov. Rep. Prague*, **7**.
(15) ROBINSON, G. W. and WILLIAMS, R. (1925). *Trans. Faraday Soc.* **20**, 586.
(16) KELLEY, W. P. and BROWN, S. M. (1924). *Agric. Exp. Stn. California, Tech. Paper*, **15**.
(17) SAINT, S. J. (1925). *Trans. Faraday Soc.* **20**, 594.
(18) CROWTHER, E. M. and MARTIN, W. S. (1925). *Journ. Agr. Sci.* **15**, 237.
(19) SALISBURY, E. J. (1922). *Journ. Ecol.* **9**, 220.
(20) CROWTHER, E. M. (1925). *Journ. Agr. Sci.* **15**, 232.
(21) WHEETING, L. C. (1924). *Michigan Agr. Expt. Stn. Tech. Bulletin*, **62**.
(22) OGG, W. G. (1927). *Proc. Internat. Soc. Soil Sci. Washington.*
(23) HENDRICK, J. and NEWLANDS, G. (1923). *Journ. Agr. Sci.* **13**, 1.
(24) SMITH, W. G. and CRAMPTON, C. B. (1914). *Journ. Agr. Sci.* **6**, 1.

(25) Smith, R. and Smith, W. G. (1900 and 1904–5). *Scottish Geog. Mag.*
(26) Macpherson, D. and Smith, W. G. (1913). *Brit. Assoc. Rep. Section M.*
(27) Smith, W. G. (1918). *Journ. Ecol.* **6**, 1.
(28) Ogg, W. G. (1926). *Scottish Journ. Agr.* **9**, 20.
(29) Arrhenius, O. (1926). *Actes de la IVème Conférence Internationale de Pédologie, Rome,* **3**, 546.
(30) Cunningham, A. (1926). Rothamsted Conferences I. "The Growing of Lucerne," **10**.
(31) Williamson, W. T. H. (1927). *Scottish Journ. Agr.* **10**, 180.

(*Received October 4th*, 1927.)

THE EFFECT OF IODINE MANURING ON THE IODINE CONTENT OF PLANTS.

By J. B. ORR, F. C. KELLY and G. L. STUART.
The Rowett Research Institute, Aberdeen.

The question of the effect of iodine manuring on the iodine content of plants has recently assumed considerable importance in view of the use of iodine as a cure and preventive of simple goitre. Whether the theory that goitre is due to deficiency of iodine be correct or not, it appears to be well established that small doses of iodine act both as a cure and a preventive of enlargements of the thyroid. It has therefore been suggested that a simple and effective method of general prophylaxis, in areas where goitre is at present endemic, might be found in increasing the iodine content of foodstuffs such as milk and eggs, by administration of iodine, and of plants by iodine manuring.

It has been shown by Orr and Leitch, at this Institute (1), and by Niklas and his co-workers at Weihenstephan (2), that the iodine content of milk may very readily be raised by administration of potassium iodide, without prejudice to milk yield, or to the health and breeding capacity of the lactating animal. Thus, for example, the daily administration of 0·18 gm. of iodine raised the iodine content of cow's milk from 6 to about 30γ per 100 c.c., and it has also been found at this Institute that the iodine content of eggs was raised from about 6γ to 140γ per 100 gm. by increasing the daily intake of iodine by 0·001 gm.

That the iodine content of plants may equally easily be raised has been shown at several different centres. In Stoklasa's pot experiments (3) with beet, the iodine content of the tubers was increased three to four times, and similar increases were found in pot experiments with several other species. v. Fellenberg (4) in his plot experiments with grass and beet found the iodine content of the plants from the plots manured with iodine about three times as high as that of those from the control plots. Scharrer and Strobel (5) have confirmed these results on sugar beet. In a series of plots with graded doses of iodine, the iodine content of the plants was increased in proportion to the dose of iodine applied, the iodine in the leaves being increased relatively more than in the roots. Similar results are reported by the same workers for spinach in the open, and for barley, oats, peas, lucerne, clover, meadow oats and meadow

foxtail in pots. Hercus and Roberts (6) record similar experiments with garden vegetables, the results in all cases showing an increase in iodine content after iodine manuring.

The only series of experiments in which iodine manuring appears to have failed, in some cases, to produce an increase in the iodine content of the plants, is that of Wrangell (7) at Hohenheim. It is claimed that in these experiments the differences in iodine content which occurred were without any relationship to the presence or absence of iodine manuring.

In view of the great importance of the supply of iodine both in human and in animal foods an investigation into this question was commenced in 1923 at this Institute. The first trials were made with plants in water culture, the conditions there being the simplest possible. In these experiments it was shown that the iodine content of plants in culture solution may be progressively increased by increasing the amount of iodine as potassium iodide, in the solution. Table I illustrates the results.

Table I.

Plants	Iodine in solution: gm. per litre	Iodine per plant: γ	Iodine per 100 gm. fresh wt. γ
Peas (1)	0	8	140
	0·00001	21	400
	0·001	155	4300
	0·01	700	25000
	0·1	1250	70000
Peas (2)	0	4	81
	0·0001	13	220
Mustard seedlings	0	0	0
	0·0001	21	700

Table II.

Iodine in plants: γ per 100 gm. dry wt.

Iodine added to soil per pot ...		0	·01 gr.	·06 gr.
Peas:	Shoots	154	200	2000
	Roots	940	2925	10960
	Fruits	32	61	424
Oats:	Shoots	52	180	1860
	Roots	484	800	12500
Radish:	Shoots	132	138	5565
	Roots	132	202	2664
Buckwheat:	Shoots	105	182	8170
	Roots	532	1165	2318
	Fruits	86	102	3240

Since, however, the conditions, with regard to the availability of the added iodine, may be taken to be different in soil, it remained to be investigated whether the same held true for plants in soil. In a second

series of trials therefore, peas; oats, radishes and buckwheat were grown in pots, the same soil, carefully mixed to secure uniformity, being used in each case. Iodine was applied as a solution of potassium iodide, either in one dose of 0·01 gm. per pot on sowing, or in six doses of the same amount at intervals, giving a total of 0·06 gm. per pot. The shoots, roots and, where possible, the fruits, were analysed separately. Table II summarises the results.

It will be seen that in each series, the iodine content of each part of the plant was increased by iodine manuring, and that the increase was in each case greater in proportion to the amount of iodine applied. These results are therefore in agreement with those of v. Fellenberg and the other workers quoted above.

In view of this accumulation of evidence Wrangell's results are difficult to interpret. The differences she records between the iodine content of plants of the same species from different pots are very much wider than those found by any other worker where the conditions of iodine supply are uniform, *e.g.* the range of variation in beet leaves from 20γ to 550γ per kg. dry weight. The only possible explanation of the lack of consistency in Wrangell's results appears to be an assumption that the soil possessed some unusual power to render the iodine unavailable for plant absorption. This might appear possible from Heymann's (8) work in which he shows that clay and peat, which contain large quantities of iodine, hold it in a form insoluble in water, and therefore possibly unavailable for plant use.

That such conditions are exceptional is, however, shown by all the other work quoted, and the general conclusion must therefore be drawn that manuring with potassium iodide affords a simple method of increasing the iodine content of food plants.

Note. The experiments in the second series were conducted by Dr Macgregor Skene and G. L. Stuart at the Botany Department of Aberdeen University. The results with regard to yield will be published elsewhere by these workers.

REFERENCES.

(1) ORR and LEITCH (1926). *Journal of Roy. Agri. Soc. Eng.* **87**, 43.
(2) NIKLAS (1926). *Biochem. Zeit.* **170**, 300.
(3) STOKLASA (1926). *Biochem. Zeit.* **176**, 38.
(4) v. FELLENBERG (1923). *Biochem. Zeit.* **139**, 371.
(5) SCHARRER and STROBEL (1927). *Angewandte Botanik*, **9**, 187.
(6) HERCUS and ROBERTS (1927). *J. Hygiene*, **26**, 49.
(7) WRANGELL (1927). *Naturwissenschaften*, **15**, 70.
(8) HEYMANN (1925). *Water en Gas*, **9**, 13th Feb.

(*Received November 11th*, 1927.)

VOLUME XVIII APRIL, 1928 PART II

THE INFLUENCE OF SOIL HETEROGENEITY ON THE GROWTH AND YIELD OF SUCCESSIVE CROPS.

BY T. EDEN
(*Rothamsted Experimental Station, Harpenden, Herts*)
AND E. J. MASKELL
(*Imperial College of Science and Technology, London*).

(With Five Text-figures.)

INTRODUCTION.

THE great variation in the yield of crops of the same variety from season to season, from place to place, and under differing systems of culture presents a problem which it has been the aim of agricultural experiments to elucidate since agriculture, in addition to being practised as a highly developed art, claimed also to rank as an applied science.

Partly because the issue was essentially practical and partly because the knowledge of the many factors at work was, in the early stages of experimentation, neither so great nor so disconcerting as it now is, the method of attack chosen was by means of field experiments; and, however great the assistance may be which other methods may contribute, it is to field conditions that the experimenter must eventually retrace his steps. In the field he will be confronted by a multitude of variables which can be conveniently though not exhaustively classified as seasonal, nutritional, and soil factors. Of these factors, since the only one which can be altered at will and which is the most readily estimable is the nutritional, the greatest amount of time and ingenuity has been expended on manurial experiments. This has led to the building up of a technique of plot experimentation which has disregarded rather than estimated the differences which seasonal and soil variation cause. Even within the bounds of a small experiment, however, the soil variation may be of a sufficiently high degree to cause discordant and anomalous results, and the task of eliminating these differences for the purpose of manurial trials is one which even yet cannot be regarded as entirely solved though rendered much easier by recent advances in plot technique. Although in the last resort many differences due to soil heterogeneity can be attributed to chemical or microbiological changes acting through the nutritional factor, they can be conveniently studied in relation to

the physical constitution of the soil because of its well-marked correlation with the factors to which reference has just been made.

The practical bias of agricultural experiments has resulted not only in the preponderance of field work but has also caused attention to be focussed upon the yield. Efforts have been concentrated on the establishment of positive or negative variations in the yield of crops according as certain specific and measurable changes in the nutritional factors were brought about. Such knowledge has been of necessity empiric and has been useful in proportion as the elimination of the soil variation factor has been successful. There remains however the complementary point of view; the analysis of how these yield changes are brought about, how the factors at work react on the complex mechanism of the plant so as to bring about these variations of which the yield is the index, and particularly the analysis of the plant integration of the factors over the growing season. Though the consideration of yield occupies a very necessary position in this paper it is the second type of analysis stressing the means rather than the end with which the investigation here described treats in its relationship to the factor of soil variation.

The methods which have been employed are more fully described later under the experimental section, but they consist of an attempt to apply under field conditions a technique of observation which has been worked out by the authors during the past three seasons. The methods are equally applicable to the problems of seasonal and manurial variation, on both of which they were employed in the first place.

UNIFORMITY TRIALS.

The study of soil heterogeneity by means of uniformity trials on similarly treated and cropped land has in the past been confined to the question of gross yields, and such trials have been of two types. The first of these is represented by the classical experiment at Rothamsted by Mercer and Hall (7) on an acre of wheat and a similar piece of mangold land. The aim of this experiment being the determination of those conditions of plot size and number by which, in the face of soil heterogeneity, reasonable accuracy in field experiments could be attained, the duration of the trial was one year only. The results obtained gave for that season a detailed and accurate representation of the soil variation as reflected in cropping power.

The second type of uniformity trial is representative of a good deal of American and Scandinavian work and consists of series of plots

cropped over a number of seasons with a variety of crops. Of the early American work that of Morgan (8) was undertaken as an experiment in plot technique. Sixty-three strips were included and the first crop was wheat, harvested in July, followed immediately by maize which was harvested in an immature condition in September.

Hansen at Åarslov (5) has long carried out uniformity trials which are a very rich source of data. It is a pity that they should be accessible only in Danish. One of the trials, comprising a block of 35 plots, extended over the five years 1907–11 and included the following crops: oats, rye, barley, roots, barley.

These two trials are chosen as illustrative of investigations on soil heterogeneity because they establish an important point, namely that, as tested by final yields, the heterogeneity contour changes from year to year and from crop to crop. A dot diagram of Morgan's data constructed to show the relation between yield of wheat on any plot and the subsequent yield of maize on the same plot gives a set of points falling roughly about a V-shaped curve, so that if we consider a group of plots having high wheat yield we find that these plots have either a very high or a very low yield of maize. It is clear that plots which behave similarly under wheat have responded in two quite distinct ways under maize, a differential effect which might be attributed to the different crops but might also be due to different seasonal conditions under which the crops were grown. Further, neighbouring plots tend to be grouped together and suggest that a definite soil drift is in operation. Hansen's more normal and complete data demonstrate the seasonal effect clearly. Oats and rye (1907 and 1908) show a marked positive correlation; rye and barley (1908 and 1909) no correlation of significance; barley and roots (1909 and 1910) no correlation; and roots and barley (1910 and 1911) a significant correlation. From the fact that the correlation of rye and roots (1908 and 1910) is satisfactory it would look as if 1909 was the abnormal year and that seasonal differences rather than crop differences and cultural variation as between different crops were responsible.

The foregoing examples raise speculations which can only remain speculations until the growth and yield of the crops concerned are analysed in conjunction with an analysis of seasonal and soil characteristics. Regarding the yield of a plot as the integration of a complex of factors, crop, seasonal and soil, it is evident that the same integration result may be given by quite different combinations of those factors. The alteration of one factor may however break up such a set into a

fresh series having quite different integration results, *i.e.* yields. A complete analysis requires an understanding of the exact manner in which such an integration is made. One aspect of this problem is the integration which can be observed during the crop growth. The scope of the investigations on Sawyer Field is to explore the possibilities of a simple field technique in providing data on this aspect of the problem.

Sawyer Field, Rothamsted.

Sawyer Field is one of the outlying fields of the Rothamsted home farm which only became available for the use of the Experimental Station in 1916. As far as is known the field had for a long period been uniformly cropped on a normal rotation. The field itself is level and was in fair condition, so that differences in productiveness would be likely to be directly attributable to genuine primary soil differences rather than to those superimposed by cultivation and cropping treatments. In 1923 an area of about two acres was occupied by a triplicated manurial trial on potatoes, the rest of the field being sown to barley. This was the first time plots had been laid out in this field and an examination of the data obtained in the experiment revealed a marked and fairly regular soil fertility slope over the two acres so occupied. Before therefore any further experimental work on this field was considered, it was thought advisable to obtain more information about the nature of the field and its suitability or otherwise for experimental plots, by devoting the rest of the area adjoining the potato experiment to a uniformity trial. The tract was at the time a clover ley and the autumn ploughing of 1924 was the earliest time possible for the inception of the scheme. To have waited till the root break, which would have ensured the land being flat, would have involved so serious a delay that the risk of encountering the effects of former cultivation lines was taken. Examination of the ground showed that these were not very pronounced and so not likely to be serious. In view however of the effect of new ridges and open furrows upon the yield of small plots, the field was laid out uniformly in lands of one chain width and each plot width made to coincide with the land width from ridge to ridge. The length of each plot was also one chain and from the point of view of yield data the trial comprised 47 plots in 8 × 6 formation except that the run of the hedge only allowed of a rank of five plots at one of the ends. The lay-out can be seen diagrammatically in the contour map of yields.

In order that information as to the physical condition of the soil might be available it was arranged with the Physical Department that

a uniformity dynamometer trial which they had in mind at the time should be done on this area, and accordingly representative furrows in each plot were ploughed with a plough to which a dynamometer was attached. In this way a measure of the resistance to ploughing was obtained for each plot[1]. For the results of that trial, the methods employed in reducing the data, and for the evidence that the draw bar pull is a reasonably constant function of soil type and condition, reference should be made to the appropriate paper (4). In further confirmation it may be stated that subsequent results of ploughing in a direction at right angles to that originally taken give readings of high correlation (0·90) with the previous season's records.

The following summary of normal farm operations and observations indicates the history of the field during the harvest year 1924–5.

Cultivations for seeding:

Sept. 15–23.	Ploughed.
Nov. 3–4.	Drag harrowed with 2-horse harrow, drilled with Red Standard wheat and harrowed in.

Manurial treatment:

Apr. 2.	Top dressed with nitrate of soda at rate of 1 cwt per acre.

Harvest:

Aug. 19–21.	Cut.
Aug. 22.	Shocked.
Aug. 31–Sept. 1.	Carted.

The tilth into which the wheat was drilled was a fair tilth notwithstanding the limited cultivation afforded to the soil. Shortly after drilling a period of wet weather caused the finer fractions of the tilth to run. After such an occurrence the action of drying winds tends to form a hard cap over the surface of the soil which hinders the establishment of a plant. This cap had one beneficial effect, it suppressed completely the growth of weeds so that to the close of the season there was never any misgiving that the differences exhibited by different plots, could be due to the competition of weeds, particularly of the graminaceous order.

The yields shown in Table I were from an area of 0·098 acre instead of the actual plot size of 0·1. These figures have been used throughout as the plot yields partly because their adoption in this form does not

[1] Resistance to ploughing is measured as draw bar pull in pounds.

affect the arguments to be adduced from the data, and partly because in this form they have been used in another connection (6). The further restriction of dealing only with the grain yields is made because of the

Table I. *Yield of grain (in* $\frac{1}{8}$ *lb.) per plot on Sawyer Field,* 1925.

	A	B	C	D	E	F	G	H
6	—	1832	1621	1579	1367	1498	1618	1300
5	1571	1532	1380	1177	602	1130	1206	1052
4	1590	1474	1651	1066	577	586	656	712
3	1532	1572	1331	1349	939	910	707	1076
2	1060	1140	1247	694	829	1150	1290	1318
1	1564	1324	992	576	828	1368	1482	1576

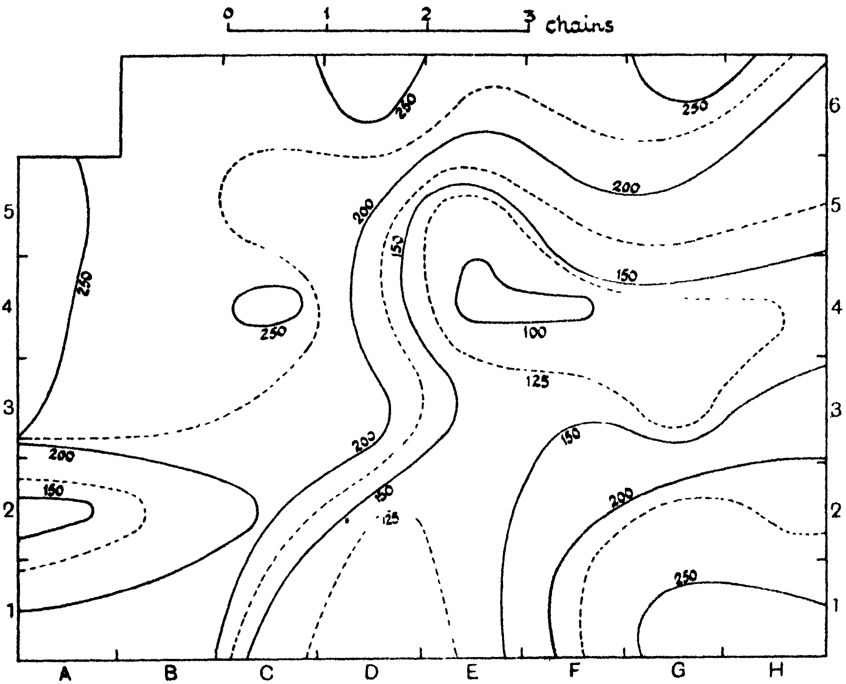


Fig. 1. Sawyer Field contour map of yield, 1925. Pounds per plot of wheat (grain).

primary importance of grain and because the remarkable correlation of 0·99 was found to exist between the grain and straw yields in this experiment by Miss Mackenzie (*loc. cit.*). Fig. 1 is a contour map of yield in pounds constructed from the data in Table I. It should be compared with the contour map of "draw bar pull" isodynes for the same area in the soil cultivation paper referring to this field to which attention has already been drawn. A casual inspection is sufficient to decide that no pronounced relation exists between the final product of

the plant and the nature of the soil upon which it grew, at any rate in so far as that relationship can be measured in terms of ploughing behaviour and tilth preparation. There is for instance a much less marked variation about the yields than there was about the physical measurements, an aspect of the results which will be dealt with in more detail later. The following data however which bear upon that point confirm in a precise manner the impression received on casual inspection of the two contour maps.

	Mean	Range	Coefficient of variation
Yield ½ lb.	1171	1832–576	3·50
Draw bar pull lb.	1374	1220–1593·5	7·33

OBSERVATIONAL DATA.

The paramount difficulty in all observational work such as that to be described lies in the choice of significant observations and in the successful prediction and calculation of the labour which will be involved at the height of the growing season; it is extremely probable that calculations based upon preliminary observations will prove to have been an under-estimate of the time required to collect comparable data at all stages of the investigations. Such proved to be the case here and consequently the data were not compiled from routine methods rigidly adhered to at all times. At different periods varying methods of counting were adopted, but all plots were treated in an absolutely comparable manner on each individual occasion. The following detailed schedule will make clear the types of observation and the methods employed over the whole course of the experiment.

When observations were commenced marked differences could be seen in the establishment of the plant, and accordingly before tillering commenced the question of establishment was investigated.

Plant number A. Between January 26 and February 5, 33 plots were examined and the number of plants upon one complete drill obtained in the following manner. Four drills were chosen at random over each plot and the number of individual plants counted. The drills ran at right angles to the ridge and furrow and were consequently all comparable. The figure used in subsequent treatment of the data is the average of these four drill row counts. Subsequently only 16 of these plots were observed and these were a random sample except for the restriction that at least one plot should occur in every numbered row and every lettered column (see contour map).

Plant number B. On April 22 another estimate of plant number on

the 16 plots referred to was made in a different manner. On this occasion a 9 ft. rod was thrown haphazardly on to the plots and aligned with that drill row which was nearest to a definite end of the rod; the number of plants was then counted on four such randomly distributed lengths.

The intention had been to determine whether in the interval the plant population had altered in consequence of environmental effects subsequent to the date of the first count. This proved not to be the case since the mean of all the plots on the first occasion was 248 and the corresponding mean for the second when expressed as plants per drill row was found to be 256. The A and B counts were therefore considered as independent estimates of the same population and the data given in the tables represent for each plot the mean of the two counts.

Shoot count 1. March 19. This count was a trial estimation rather than a count. It is possible with experience to estimate with tolerable accuracy the percentage of the plants with 1, 2 or 3 tillers, etc., in localities of small dimensions such as experimental plots afford. When more than one person is engaged in the same estimation the figures take upon themselves a considerable degree of reliability. On this occasion the plots were classified according to the percentage number showing a first tiller T_1, and both first and second, T_1 and T_2. The correlation with plant number of the tiller coefficient derived from the sum of T_1 and T_2 values was so marked as to justify the conversion of these values into a value for total shoots per row (including T_0) based upon the average plant number. On the same date total height of plant and width of the topmost fully unrolled leaf was determined on the plants.

Shoot count 2. April 22. This was carried out on the 9 ft. rod rows described under the heading for plant number B. Leaf breadth was also estimated as formerly.

Shoot count 3. May 28 as on April 22. Other data obtained were shoot height, *i.e.* height to the auricle of last leaf, and total height.

Shoot count 4. July 24, on chain rows. On this occasion only ear-bearing shoots were counted. In the table this count is briefly described as ears.

These complete the observations in the field and all the field data have been converted into the comparable form of population per drill row of one chain. To conclude the account of the primary data mention must be made of the bushel weight and the 1000 corn weight, the latter determined in duplicate. Before passing on to the consideration of the data attention is drawn to the ratio of shoots to plants in the section

devoted to derived data in the table on p. 172. These are all calculated on the average plant number.

EXPERIMENTAL DATA.

The work of Engledow and Wadham (2) has shown the important effect of tillering upon the yield of a grain crop and although in many cases the tillers develop no ears the number and behaviour of the tillers are a valuable indication of the robustness and general growth capacity of the plant. There is also a close correlation in the early stages of the life of the plant between tillering progress and other morphological growth characters. It was because tillering gives evidence of being the main factor in the determination of the yield of any given plant population that the development of the data for this paper is restricted to the consideration of that aspect of plant behaviour. It is moreover the one character which remains constant in type throughout the whole season as distinct from total height for instance, which at one period changes almost entirely by virtue of elongation of leaf length and at another time by virtue of the elongation of internodes without a corresponding increase in leaf elongation.

Table II gives the data for the 16 plots upon which the whole series of measurements has been carried out. The primary data represent the result of actual counts on a plot basis and the derived data refer to the average plant.

THE EFFECT OF THE PHYSICAL FACTOR.

The first survey of the crop with respect to the establishment of plant revealed differences which were probably as great as any that are likely to be obtained in an area so small. The plant was nowhere very thick; for the highest number of plants obtained represents only a little more than 50 per cent. of a good wheat plant in an agricultural sense, whilst the poorest was absolute failure from the farmer's point of view. The variation can be readily seen on inspection of the figures and the standard deviation from the mean. This was an effect due in all probability to the interaction of tilth, at time of sowing and subsequent weather, on the germination and early development of the seedlings. At the time of counting the whole field was at the seedling stage, and evidences of a high mortality of seedlings which had experienced fairly normal germination were not wanting. The ploughing draught data provided an integrated measure of physical variations in the soil, and although tilth itself is an elusive factor to measure or even define, the

Table II.

	Primary data										Derived data				
Plot	D.B.P. lb.	Average plant No.	Shoots Mar. 13	Shoots Apr. 22	Shoots May 28	Ears July 24	Yield grain $\frac{1}{8}$ lb.	Bushel wt. lb.	1000 corn wt. gm.	Space per plant inches	Sh./Pl. Mar. 19	Sh./Pl. Apr. 22	Sh./Pl. May 28	Sh./Pl. July 24	Yield per plant gm.
A 1	1235	379	664	1416	1075	570	1564	57·63	42·92	2·09	1·75	3·74	2·84	1·50	2·340
B 3	1279	370	601	1015	1258	639	1572	57·25	39·88	2·14	1·65	2·75	3·40	1·73	2·408
C 1	1300	263	388	704	867	421	992	57·88	43·70	3·01	1·475	2·68	3·30	1·60	2·138
C 5	1416	277	457	673	671	490	1380	58·38	44·22	2·86	1·65	2·43	2·42	1·77	2·825
D 3	1357	298	425	762	1060	569	1349	57·75	40·82	2·66	1·425	2·56	3·56	1·91	2·565
D 5	1584	136	156	418	730	292	1177	57·81	48·40	5·82	1·15	3·08	5·37	2·15	4·908
E 1	1347	193	251	435	786	344	828	58·00	44·14	4·10	1·30	2·25	4·07	1·78	2·432
E 4	1519	97	107	161	373	197	577	58·75	45·38	8·17	1·10	1·66	3·85	2·03	3·372
E 5	1589	114	129	248	468	223	602	58·75	46·54	6·95	1·15	2·17	4·11	1·96	2·995
F 1	1280	341	630	874	1230	538	1368	58·00	43·16	2·32	1·85	2·56	3·61	1·58	2·274
F 5	1528	166	203	465	749	384	1130	58·88	46·26	4·77	1·225	2·50	4·51	2·31	3·859
G 3	1356	268	442	531	601	328	707	58·38	43·98	3·00	1·65	1·98	2·24	1·22	1·495
G 4	1350	142	202	378	388	150	656	58·75	46·36	5·58	1·425	2·66	2·73	1·06	2·620
H 1	1220	437	917	1314	1342	630	1576	57·83	44·56	1·81	2·10	3·01	3·07	1·44	2·044
H 2	1244	336	621	863	1162	511	1318	58·25	43·62	2·36	1·85	2·57	3·46	1·54	2·223
H 4	1359	217	288	548	588	253	712	58·75	44·90	3·65	1·325	2·53	2·71	1·17	1·861
Mean	1372	252	450	675	834	409	1171	58·19	44·30	3·83	1·505	2·57	3·45	1·67	2·656
σ	121·8	104	238	356	302	160	410	00·49	8·20	1·91	0·294	0·47	0·81	0·35	0·830

stubborn and "unkind" areas that went down with difficulty into a seed bed were also those offering the most resistance to the plough. There is indeed, as Fig. 2 shows, a remarkable correlation between

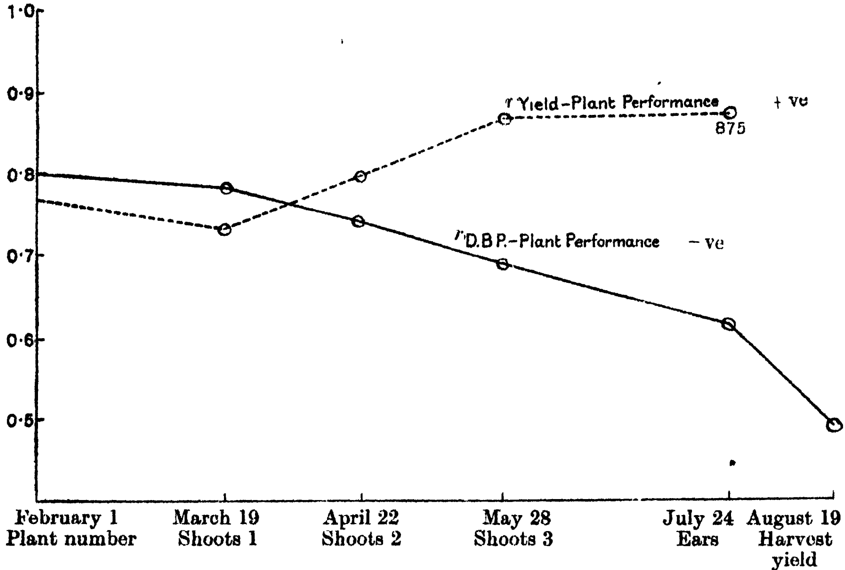


Fig. 2. Sawyer Field wheat, 1925. Correlations of plant performance.

ploughing draught and plant number in the first instance; the correlation in question forms the first point in the ploughing draught plant-performance curve. Whatever underlying soil factors ploughing draught may measure in reality, it is safe to say that these were almost completely the factors which determined tilth and germination on the one hand and soil behaviour under varying weather conditions later. This is an important correlation since it establishes a physical measurement on a field scale which has both an agricultural and a plant physiological significance.

Further consideration of the behaviour of the growing plant shows that this influence of initial physical conditions is by no means short lived. On March 19, when total shoots per plot were estimated, the effect of this factor had not even diminished by any significant amount.

On general grounds it is surprising to find that the correlation between shoots and ploughing draught stands so high. In this case it also indicates a high correlation between plant number and shoot number at the later date. Bearing in mind the great variations in space which the plants on different plots had, no surprise would have been occasioned by the diminution of the value of r by reason of the added facilities for

tillering for which the larger spacing gave opportunity, a factor which would work in opposition to that affecting plant number. In point of fact however this result shows two things, firstly that the spacing was nowhere insufficient and that no competitive hindrance to tillering was in operation, and secondly that leaving spacing out of account altogether the intensity of the relatively good or relatively bad soil conditions as measured by ploughing draught was still unimpaired; the primary condition of tilth had indeed been the main factor at work for nearly five months. During the rest of the season the effect of the physical factor, inasmuch as ploughing draught is a measure of it, is seen to decrease in progressive tiller counts at a steady rate until ear-bearing tillers are reached; after this there is a steep decline to $-0{\cdot}492$, the value for r ploughing draught-yield. The latter value is just not significant according to Fisher's table of significance (3).

The sudden drop in the correlation coefficient for yield data is not untoward, since despite the close relationship between tillering and yield the former does not completely account for the observed variation in yield, nor therefore can any factor closely correlated with tillering be expected to do so. As regards the other correlations, however, the constancy of the diminution does suggest that the underlying cause is a factor which is itself making constant progress against the effects of the soil conditions previously discussed. The identification of the factor and its measurement are discussed in the next section.

Referring now to another aspect of the data, as plant performance deviates more and more from expectation (if tilth and early condition are taken as criteria) each successive stage in the growth of the crop affords an increasingly more accurate prediction of the final result. Yield and plant performance show a high and significant correlation throughout, and this correlation is steadily improved as time goes on. The two correlation coefficient curves show how very divergently the plant performance and the physical conditions of the soil are operating.

The Spacing Effect.

The data immediately suggest that spacing is the cause of the compensating effect thus demonstrated. As soil temperature rose and the waterlogged condition of the soil mended, the plant commenced to grow, and, at the tillering stage, the space available for each individual plant increased in importance. Those plots which had experienced the more severe failure in plant now had an advantage which in this case was so great that previous unfavourable conditions were largely counter-

balanced. The general effect is shown simply in Fig. 3. In the construction of this diagram the 16 plots were divided into groups of four on the basis of plant number, and the shoot/plant ratio on the several

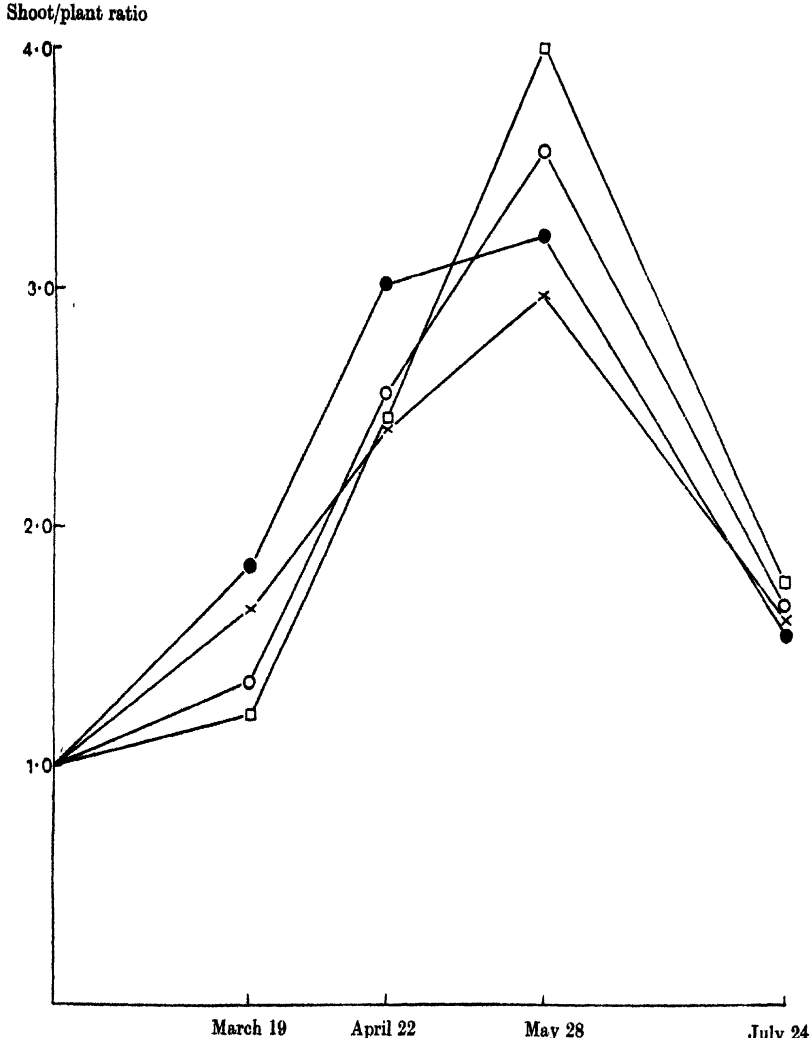


Fig. 3. Sawyer Field wheat, 1925. Tillering progress: plots arranged in groups according to initial number of plants per row.

occasions plotted against the time intervals. On the first occasion when shoots were counted the ratios were in the same order as the plant numbers of the four quarters, so that the number of tillers per plant

was greatest where space was least; up to this period the same factors which produced poor establishment of plant continued to affect adversely the tillering of the survivors. Had this effect continued the correlation between the plant performance and the physical factor would have been considerably intensified. The shoot numbers rose to a maximum in the neighbourhood of 5 per plant and then fell off by the dying of the weaker shoots. The final ratio represents ears per plant. In the course of this rise and fall the relative position of the four groups changes till finally the plots showing the better plant show fewer shoots per plant.

It was this complete change in the growth potentialities of the individual plants which reduced the yield-draught correlation, and as the process became intensified that of yield-plant performance. It was not however able to impress itself so strongly as to outweigh the advantage to the plot derived from the superior stand of wheat in closer array.

The correlations tabulated in Table III show the change on an average plant basis in a decided fashion.

Table III. *Correlations of plant performance on basis of average plant of wheat.*

	(1) Space	(2) Ploughing draught	(3) Sh./Pl. 1	(4) Sh./Pl. 2	(5) Sh./Pl. 3	(6) Sh./Pl. 4	(7) Yield per* plant
(1) Space		+·786	−·784	−·480	+·455	+·573	+·573
(2) Ploughing draught			−·788	−·388	+·565	+·616	+·727
(3) Sh./Pl. 1				+·377	−·530	−·478	−·572
(4) Sh./Pl. 2					−·001	−·154	+·039
(5) Sh./Pl. 3						+·752	+·762
(6) Sh./Pl. 4							+·517

As the season proceeds the correlation of yield and plant performance changes in magnitude and sign. Starting negative and relatively high at the early tillering stage (Sh./Pl. 1) it becomes non-existent at the second stage and then increases greatly up to the time of maximum tillering. Similarly one can trace the change in tillering itself. Ear formation was negatively correlated with the first stage of tiller formation, less markedly so with the second, and positively so with the third.

At this stage an interesting fact may be noticed with regard to the yield correlations. It has already been pointed out with reference to the plots that the spacing effect steadily decreased the dependence of plant performance on initial soil conditions, and that the falling off was great when one passed from ears per plot to plot yield. This was so since yield measured the effect of factors and processes not covered by

a census of ears which takes no account of whether the ear be large or small, well filled or empty. Further light is shed on this by the yield per plant correlations. Reference to that series shows that the correlation between yield per plant and maximum tillering (Sh./Pl. 3) is greater than that for yield and ears. This is demonstrated also by Engledow for barley (1). The present experiment thus affords confirmation of the view expressed by Engledow that maximum tillering capacity is an indication of the vigour of the plant in all directions and thus reflects its capacity for growth and development in a very remarkable way. Mention may here be made of the effect of the spacing factor on the size of the grain. There is a definite if not large negative correlation between the yield per plot and bushel weight. This may be due either to superiority in grain weight and size in the low yielding plots, or to a smaller grain packing more tightly into the same volume. In the first case a positive correlation between bushel weight and the weight of 1000 corns would be expected whilst the second alternative would need a negative correlation. Inspection of a dot diagram shows a positive correlation.

Broadly speaking the plots which produced poor yields on account of thinness of plant were able to make superior sized grain, and the higher yield per plant on these plots is attributable to this as well as to the superiority in number of ears.

THE EFFECT OF PREVIOUS HISTORY ON DEVELOPMENT.

The direct correlation of stages in plant development with previous stages gives no indication as to how those correlations have been built up. In point of fact the condition of the plant at any time is determined by its previous history and it becomes of some interest to determine to what extent various stages of growth have independently modified the progress toward the final performance of the plant. The correlation between any two successive estimates of shoot number expresses not only the result of factors operating during the intervening period, but over the whole growing season, involving in this case factors which have at times been competitive and still leave their mark.

There does not appear to be any established method of analysis for this particular point, for the resolution for example of the nett effect of the spacing factor during a given interval irrespective of the previous history of the plant. In the absence of a method of proved validity the data have been treated by a method which seemed to offer an approximate answer to the information required. The correlation between any

two stages of growth independent of the effect which previous history (as reflected by previous growth measurements) has had can be theoretically deduced by establishing partial correlations between the two sets of measurements, all other variables being assumed constant.

Thus r for ploughing draught and shoot number per plot on March 19 is high owing mainly to the effect of plant number which is itself very closely related to the ploughing draught. A partial correlation between shoots and ploughing draught, the effect of plant number being eliminated, would show how small was the causal relationship between the two first. On these lines two sets of "cumulative" partial correlations have been deduced, one on a plot basis and another on the basis of the behaviour of the average plant.

The first demonstrates the relationship between yield per plot and selected important characters and factors in the promotion of plant growth.

The selection made was as follows:

(1) Yield.
(2) Ears.
(3) Maximum number of shoots.
(4) Plant number.
(5) Ploughing draught.

The cumulative direct partial correlation coefficients between yield and successive factors are thus:

$$r_{15} = -\cdot 492, \qquad r_{13.54} = +\cdot 653,$$
$$r_{14.5} = +\cdot 723, \qquad r_{12.543} = +\cdot 257.$$

The notation is that usually employed by Yule and is to be interpreted as follows:

$r_{14.5}$ = correlation coefficient between yield and plant number, ploughing draught being constant.

These figures suggest several important relationships. They show decidedly that plant number, with its positive correlation highest of all, is the main factor in the yield performance of these plots. Favourable as were conditions for tillering during the later stages, tillering did not exert so pronounced an effect on the final product as the establishment of a good plant, although the actual direct correlation of ears to yield as against plant to yield was higher (+ 0·875 to + 0·730). Capacity to form ears served but slightly to modify the expectations indicated by previous history. We may picture therefore the plot population growing from its earliest stages as being more difficult to move out of its predestined course; each successive wave of events being less effective than its predecessor.

Turning to the average plant a rather different view-point was taken since the performance of the individual plant was profoundly affected by the spacing effect; since, too, the intensity of this factor was great enough to reverse the tillering capacity of the plots, the progressive effect of spacing was subjected to the analysis by cumulative partial correlation coefficients. Space was measured as the reciprocal of plants per chain. The following values were obtained:

(1)	Space	$r_{12} = +0{\cdot}786$
(2)	Ploughing draught	$r_{13.2} = -0{\cdot}431$
(3)	Sh./Pl. 1	$r_{14.32} = -0{\cdot}283$
(4)	Sh./Pl. 2	$r_{15.432} = -0{\cdot}036$
(5)	Sh./Pl. 3	$r_{16.5432} = +0{\cdot}298$
(6)	Sh./Pl. 4	$r_{17.65432} = +0{\cdot}392$
(7)	Yield per plant	

There is here more clearly shown the progress of the compensation effect. At the initial stages spacing appears unfavourable for tillering but becomes less so. Actually it cannot be conceived that at the initial stages space *per se* was a vital factor at all. The residual correlation even after the effect of ploughing draught has been eliminated can only mean that the thinness of plant was linked up with an inhibitive factor not completely accounted for in the ploughing draught measurements. The intricacies of tilth production and behaviour are such that such a result is readily understandable. Once spacing begins to have a positive effect that effect appears to grow progressively more pronounced. As far as the analysis goes it suggests that the result of more space per plant with consequent larger air, light, and root range was more beneficial as time went on and produced its maximum effect as late as the filling of the ears and corns. In the course of calculating the required partial coefficients one peculiar value was obtained. This is $r_{72.13456} = +{\cdot}638$. This is virtually a correlation between yield and plough draught after eliminating the whole effect of growing the plant up to ear formation. If it means anything it is that the heavier soil condition had a positive effect on yield during the final stage of growth.

A further method of showing the cumulative effect of the previous history of the plant upon its ultimate performance can be obtained by a graphical representation of the variance determined by the correlation coefficient of yield and plant characters as measured by their squares (Fig. 4). Unity represents complete success in predictability of the final yield and the fractional values ascribed to r^2 and $1 - r^2$ represent the

validity of the prediction from any of the yield plant performance correlations. Successive characters show a gain in accuracy in prediction, and some measure of the increased gain as these successive characters become available for measurement is to be had by comparing the increment in the value of r^2 from one to another. In the figure the values are shown as blocks approaching unit value. An extra stage has been introduced into this analysis obtained not from the primary data but from the derived data of Table II. The number of grains per plot was calculated from the yields per plot and the weight of 1000 corns. The

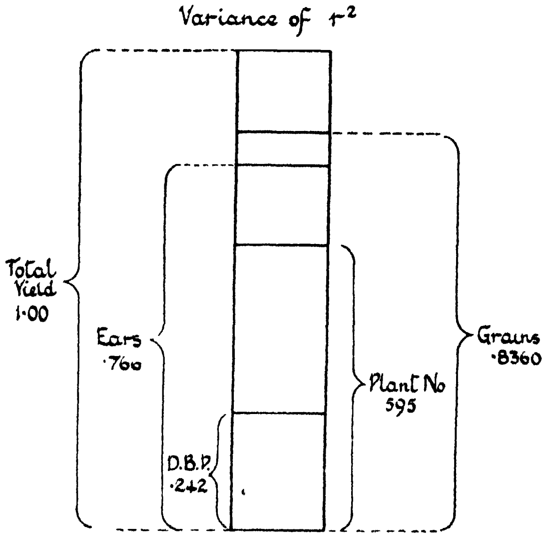


Fig. 4. Sawyer Field wheat, 1925.

indications are that plant number makes the largest individual contribution, with ears and grain size also contributing appreciably. A knowledge of the number of grains according to this scheme effects very little improvement in the prediction.

The progressive compensation effect in its relation to the previous history of the plant is well demonstrated by the relative variance per cent. $(\sigma/M)^2 \times 100$, where σ is the standard deviation of all the plots and M is the mean. By expressing the data in this way measurements of varying kinds can be compared. Fig. 5 is a block diagram of this function. The high degree of variability in the plant numbers at the commencement of the season is reflected in the value 17·03 per cent. for that character. By the time the plant has come into ear, spacing

compensation has reduced that variance by nearly 2 per cent. and a similar levelling up occurs in the filling of those ears both in number of grains and in their size. At the time of harvest 5·6 per cent. of the variance has been eliminated which represents almost one-third of the total. The parts played by the ear, grain number, and grain size in

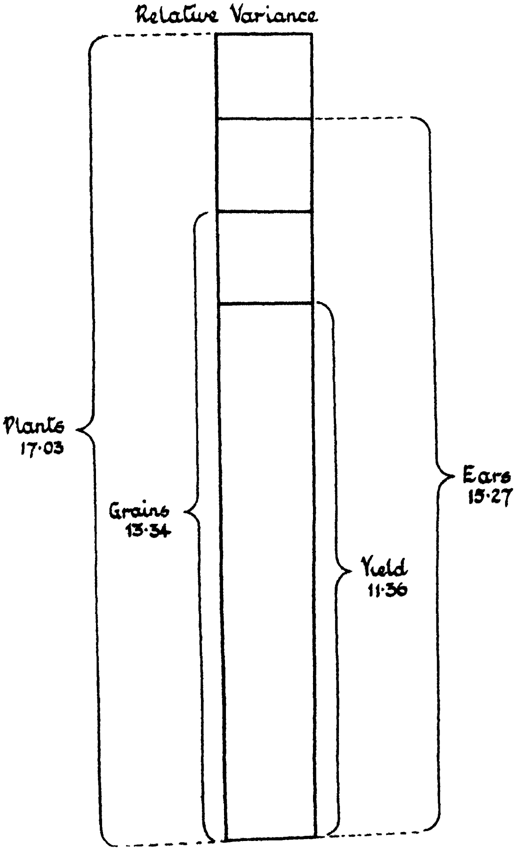


Fig. 5. Sawyer Field wheat, 1925.

the compensation are according to relative variance per cent. measurement about equal in importance. This result does not altogether square with the previous and analogous indication in predictability, but the latter is admittedly only an approximate estimate.

This section may be summed up by saying that the measurements here tabulated do in a marked degree demonstrate the effect of physical conditions on the development of the plant and the enormous recu-

perative power possessed by the plant under favourable spacing conditions. They further show on analysis the *modus operandi* of the compensation and the limits within which such action can effectually operate.

EFFECT OF SOIL HETEROGENEITY ON THE ROOT CROP.

In 1926 after a winter fallow Sawyer Field was put into swedes. In the meanwhile the field had been ploughed out of the stubbles in the same direction as at the commencement of the experiment and reploughed across these stubble furrows. It was then manured with 20 loads of farmyard manure to the acre and ridges drawn out parallel to the new line of ploughing. The drills were accordingly in the same direction as the wheat drills of the previous year. Thirty ridges were made to each plot. The crop was sown on June 14, 1926, under excellent conditions and singled between July 16 and 20. The swedes were pulled between November 4 and 27.

This crop presented such fundamental differences from the preceding one that observations upon it were continued in much the same way. The contrasts between the two crops are tabulated below.

Wheat	*Swedes*
Winter crop	Spring crop
Rough shallow tilth without manure	Fine deep tilth with manure
Slow germination	Quick germination
Crop subject to spacing compensation	Crop artificially spaced

Attention was concentrated upon the difference which more uniform tilth conditions at seeding and the absence of competitive spacing might produce. The crop is however a more difficult one on which to make quantitative measurements, and the task was begun without any previous experience either of the type of observation likely to reflect adequately the real progress of the crop, or the numbers of individual observations necessary to give reliable data. The following measurements were carried out either on the whole field or the 16 plots observed during the previous season as specified.

(1) Germination count on 16 plots. June 25. The average of 10 metre row lengths per plot. The counts were compared with the known delivery of the drill ascertained by a triplicate set of trial deliveries over a length of 5 chains and by a quadruplicate 1000 seed weight.

(2) The length of the oldest green leaf in cm. on 16 plots. 150 plants (5 per row) chosen at random in the row August 13.

(3) Diameter of bulb. 100 bulbs per plot, October 6 on 16 plots. For this estimation the sizes were grouped into a number of ranges measured by means of gauges similar in pattern to wire gauges. Each

gauge was nine-tenths of the size of the one preceding it. In this way the error of measuring bulbs of varying sizes was minimised. The numbered gauge into which the root would just fit was taken as the correct one. The scale was an arbitrary one.

(4) Total number of roots per plot (47 plots).

(5) Yield of roots and tops (47 plots).

These measurements have not been so productive of significant correlations as was the case with the wheat crop. That this is due to the totally different conditions is highly probable, but it is also perhaps due to the fact that the technique of measurement was not adequate.

Germination was almost uniformly good. An average of 66 seeds was sown per metre; the highest germination was 60 per metre row (90 per cent.) and the lowest 47 (71 per cent.) with a mean of 53 (80 per cent.). No significant correlation between primary physical soil conditions (ploughing draught) was observed, the value of r being $+ 0{\cdot}275$, whilst a 1 in 20 probability of the correlation being a spurious one gives a limiting value as high as $0{\cdot}4973$.

Table IV. *Yield of swedes (roots) in lb. per plot and number of swedes (italics).*

Plot	A	B	C	D	E	F	G	H
6	—	3608	3936	4372	4488	4264	4436	4120
	—	*1716*	*1689*	*1688*	*1665*	*1737*	*1674*	*1841*
5	4080	4228	4452	4566	4594	4443	4504	4624
	1559	*1559*	*1655*	*1667*	*1678*	*1694*	*1708*	*1540*
4	4056	3988	4188	4296	4327	4420	4402	4435
	1507	*1593*	*1554*	*1528*	*1530*	*1596*	*1480*	*1499*
3	4056	4046	3996	4106	4292	4108	3950	4128
	1506	*1148*	*1502*	*1448*	*1474*	*1542*	*1497*	*1484*
2	4224	4164	4228	4284	4276	4004	3956	4019
	1497	*1416*	*1519*	*1182*	*1452*	*1438*	*1410*	*1362*
1	3811	4172	4019	4279	3547	3231	4143	3807
	1360	*1362*	*1394*	*1379*	*1387*	*1355*	*1474*	*1534*

	Roots		
Summary:	lb.	tons	No.
Average yield per acre	41675	18·6	15335
Standard deviation	2793	1·2	1179
Standard deviation per cent.	6·7		7·7

The actual final yield of roots gives a correlation of $+ 0{\cdot}508$ with ploughing draught which is quite significant (the corresponding level of significance for 47 pairs of observations being $0{\cdot}2875$) but is not high enough to suggest a predominating influence. The yield was surprisingly uniform over the 47 plots. The most significant interdependence of all is between ploughing draught and number of roots. This is an interesting

correlation upon which the method of singling throws light. Owing to the magnitude of the root acreage it was necessary to adopt unconventional means in 1926 in order to carry out the singling process at approximately the correct time. Actually this and other fields were "bunched" by using a cultivator upon which had been fixed ducksfoot tines of large dimensions grouped together at convenient distances. This implement was dragged across the rows and hand singling was started on immediately afterwards. The variation in root number which resulted is a consequence one would suppose of the fact that roots which were insufficiently uprooted by the process re-established themselves. The correlation between number of roots and ploughing draught of +0·671 can be explained as the result of the cultivator tending to "ride" and come out of its work on the more resistant soil. It may be that in the dry period of weather following singling the greater retention of moisture by the heavier soil also helped the re-establishment of only partially eradicated plants, but probability favours the cultivator explanation. The added number of roots helped the yield but little, most of the supernumeraries being small in size. .

Table V. *Growth measurements on* 16 *plots.*

	Germination per 10 metre row	Length of leaf	Bulb width index (arbitrary)
A 1	467	53·36	50
B 3	505	53·61	81
C 1	540	55·58	89
C 5	583	55·44	64
D 3	550	57·39	66
D 5	511	56·33	64
E 1	361	53·64	75
E 4	523	59·75	55
E 5	614	57·29	46
F 1	523	55·53	55
F 5	595	58·44	39
G 3	515	55·41	84
G 4	533	59·01	59
H 1	470	61·90	63
H 2	686	61·74	83
H 4	531	59·24	21

Table VI. *Correlations of plant performances of swedes* (47 *pairs*).

1 = Yield of swedes	$r_{13} = + \cdot 508$	$r_{12.3} = + \cdot 128$
2 = Number of roots	$r_{23} = + \cdot 671$	$r_{13.2} = + \cdot 335$
3 = Ploughing draught	$r_{12} = + \cdot 423$	
4 = Germination	$r_{15} = + \cdot 567$	
5 = Yield of wheat	$r_{34} = + \cdot 275$	(16 pairs)

The partial correlations show that the chief influence in the relationships between soil condition and yield variation was the number of roots left in the ground.

Comparing the wheat yields and root yields a significant positive correlation emerges of + 0·567.

A number of other contrasts were examined and dot diagrams for the interdependence of bulb size and ploughing draught, bulb size and yield, bulb size and length of leaf, proportion of leaf per plant to quantity of root, were prepared but inspection showed that no correlation could be established.

SUMMARY.

1. The interaction of physical conditions of the soil and the establishment of plant together with its subsequent growth and yield have been studied for wheat and swedes on a variable piece of land, maintained as a uniformity trial.

2. Ploughing draught was taken as a criterion of the physical condition of the soil and various simple measurements on the crop were made from time to time during growth.

3. The establishment of wheat showed substantial negative correlations with ploughing draught but the correlations between ploughing draught and the performance of the plant diminished as growth progressed. This was shown to be the result of the overwhelming importance of the spacing factor operating beneficially on plots where the plant was abnormally poor. The effect of this factor is traced step by step.

4. Swedes differing from wheat in almost every detail of cultivation and growth cycle showed no correlation between soil conditions and germination or between the various growth stages and physical soil conditions. The highest significant correlation was between the number of roots per plot after singling and ploughing draught and an explanation of this is given.

5. There was a significant but only moderate correlation between the yields of the two crops.

REFERENCES.

(1) ENGLEDOW, F. L. (1926). *Journ. Agric. Sci.* **16**, 166.
(2) ENGLEDOW, F. L. and WADHAM, S. M. (1924). *Journ. Agric. Sci.* **14**, 66.
(3) FISHER, R. A. (1925). *Statistical Methods for Research Workers*, 174.
(4) HAINES, W. B. and KEEN, B. A. (1925). *Journ. Agric. Sci.* **15**, 387.
(5) HANSEN, N. A. (1914). *Tidsskrift for Landbrugets Planteavl.*
(6) MACKENZIE, W. A. (1926). *Journ. Agric. Sci.* **16**, 275.
(7) MERCER, W. B. and HALL, A. D. (1912). *Journ. Agric. Sci.* **4**, 107.
(8) MORGAN, J. O. (1908). *Journ. Am. Soc. Agron.* **1**, 58.

(*Received September 17th*, 1927.)

THE SPECIFIC CONDUCTIVITIES OF SOIL EXTRACTS.

By C. H. WRIGHT, M.A., F.I.C.
(*Agricultural Department, Nigeria.*)

(With Two Text-figures.)

Introduction.

Dr Mason and the author (2) determined the specific conductivities of 1 to 5 soil extracts with soil samples taken during September, October and December, 1924, from some of the cotton plots on which we were working at Oyo and Ilugun. In many cases we found only small differences between the specific conductivities of the soils from the same plot, which were probably due to the variability of the soil in the field and the difficulty of obtaining representative samples for the determinations. But there was a decrease in conductivity between September and December in many of the Oyo soils and a marked decrease in conductivity in three of the Ilugun soils between November and December, which we attributed to the removal of electrolytes by the growing crop. We also found relations between the mean specific conductivity of the November and December samples and the number of open bolls per acre for American and native cotton, which could be expressed as follows. If K = the mean specific conductivity of the November and December samples $\times 10^6$ mhos (reciprocal ohms) and N = the number of open bolls per acre $\times 10^{-3}$, then $N = 18{\cdot}74\ K^{0{\cdot}37}$ for American cotton and $N = 8{\cdot}73\ K^{0{\cdot}63}$ for native cotton.

G. R. Stewart and J. C. Martin (5) determined the conductivities of 1 to 2 soil extracts during the growth of crops. The same kind of soil (a silty clay loam) was sifted into 8 containers each 30 in. wide, 60 in. long and 18 in. deep, in 7 of which various crops were grown. The other container was uncropped and served as a control. Soil extracts were prepared from these at intervals of one or two weeks throughout the growing season. It was found that the specific resistance of the uncropped soil remained nearly uniform; but there was an increase in specific resistance, *i.e.* a decrease in the specific conductivity, of the extracts prepared from the cropped soils during the growth of all the crops. Maize (corn) increased the specific resistance of the soil extracts

more rapidly than the other crops. The containers used in the above experiments are more fully described by Stewart (4). They were covered by waterproof canvas, which was kept on during the season of heaviest rain, and the soils were kept at their optimum moisture content by the addition of distilled water only.

In view of the above facts it was thought desirable to investigate the extent of variation of the specific conductivities of soil extracts with rainfall and crop; and to ascertain the relations, if any, between the specific conductivity of the soil extract and the fertility of the soil.

Methods.

Samples of soil were taken every 28 days for one year from the same ridges on several experimental plots on Moor Plantation, the headquarters of the Agricultural Department; soil samples were also taken every 28 days from some of the former cotton plots at Ilugun referred to above. The air-dried samples of soil after removal of stones were ground up till they passed a 1 mm. sieve. All the soil extracts were prepared in the same way. Ten gm. of each soil sample were transferred to 250 c.c. Duro glass Erlenmeyer flasks with waxed corks; 50 c.c. of distilled water from a pipette were added to each flask at 5 p.m., and the flasks were then shaken. After again shaking at 7 p.m. the soil extracts were allowed to stand till 9 a.m. next morning, when they were filtered through Swedish filter papers No. 1 F into similar flasks, and the specific conductivities determined by Kohlrausch's method, using a Wheatstone bridge and dial resistance box. All determinations were made at 0° C., and all the results are stated as 10^{-6} mhos. The conductivity of the distilled water used varied from 1·1 to $2{\cdot}2 \times 10^{-6}$ mhos; but no correction was made for this, since it is about equal to the experimental error in determining the specific conductivity.

Extent of variation of Specific Conductivities of Soil Extracts.

Considerable differences in the specific conductivities of different plots at any one time of the year have been found; and also considerable differences on any one plot at different times of the year, the specific conductivities being highest in March (the end of the dry season) and the lowest in June or July (the rainy season). Hence it is only possible to compare different soils, when samples of these soils are taken at the same time of the year.

Fig. 1 shows the extent of variation with crops and rainfall of the specific conductivities of 1 to 5 soil extracts prepared from samples taken every 28 days from 4 plots on Moor Plantation, together with the rainfall during the previous 28 days. *D* 3, plots 5 and 7, are 2 out

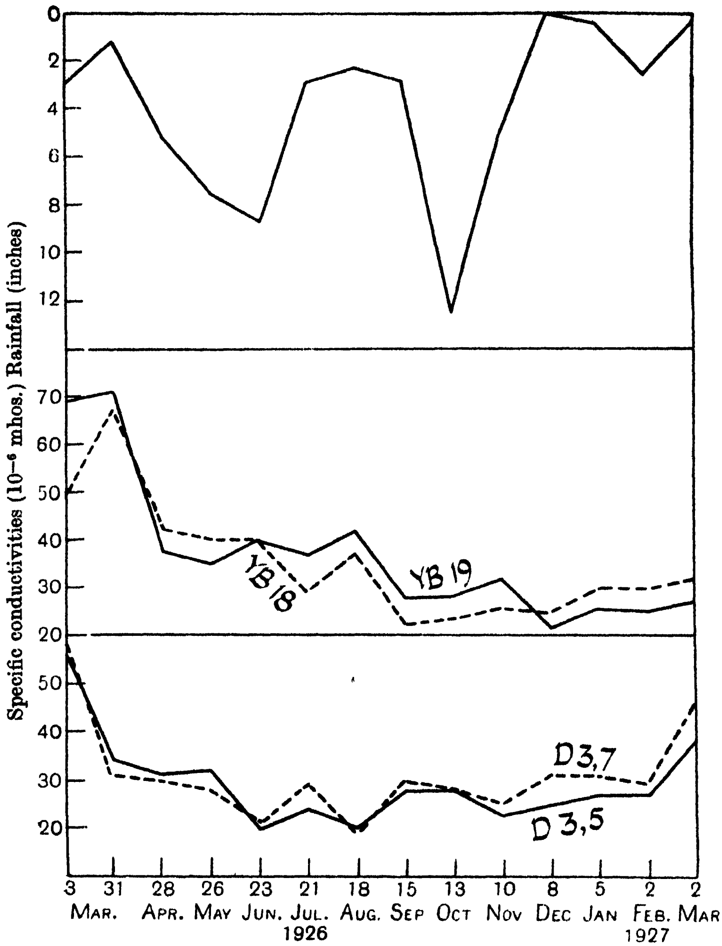


Fig. 1.

of 8 plots on the Two-Year Rotation. These plots were under early maize (sown on April 22 and harvested on August 11) followed by late maize (sown on August 30 and harvested on December 20) after the plots had been re-ridged. *YB*, plots 18 and 19, are two adjoining plots on the Four-Year Rotation. *YB*, plot 18, was under *Mucuna* (a legu-

minous crop used as green manure), which was sown on March 8 and buried green on June 22; Ishan cotton was sown on the new ridges on July 15 and was uprooted in the middle of March. *YB*, plot 19, was under groundnuts sown on March 8 and reaped in August; Ishan cotton was sown between the groundnuts on July 13 and was uprooted in the middle of March. Although the conductivities during the dry season were higher than those during the rainy weather, there is no

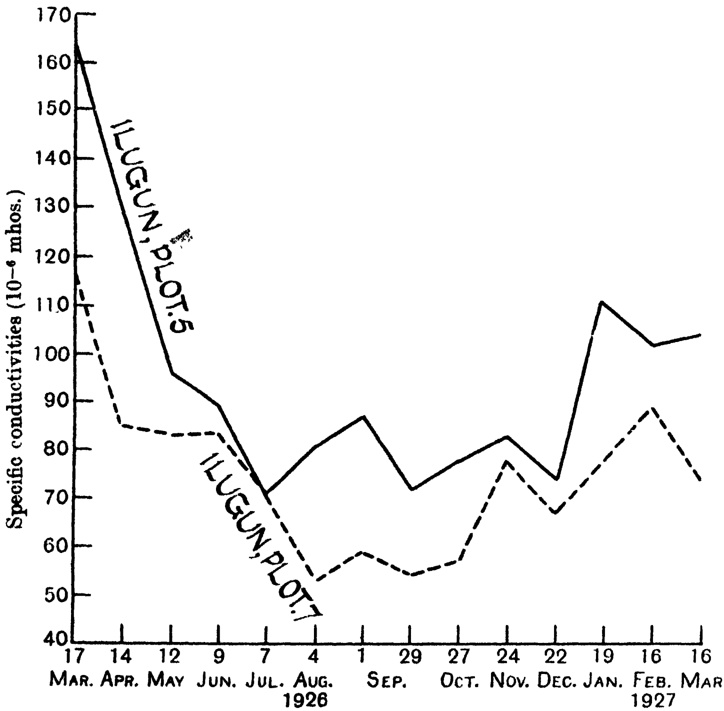


Fig. 2.

clear relation between rainfall and conductivity. Whether one exists, but is masked by removal of electrolytes by the growing crop cannot be decided from the available data. But this explanation is rendered probable by comparing the changes in conductivities on the above 4 plots from January 5 to March 2. During this period *D* 3, plots 5 and 7, were fallow, and it will be seen that after the rain in January there was a considerable increase in conductivity. During the same period *YB*, plots 18 and 19, were under cotton; the rain in January produced a vigorous secondary growth, and it is probable that the

smaller increase in conductivity is due to removal of electrolytes by the cotton.

Fig. 2 shows the changes in specific conductivity on plots 5 and 7 at Ilugun, two of the former cotton plots now under native cultivation. These two plots are 15½ and 17 miles from Moor Plantation and are on much "heavier" types of soil. It will be noticed that though the specific conductivities of the soil extracts are much higher than those on Moor Plantation, they undergo similar changes with crop and rainfall. Unfortunately rainfall records for these plots are not available; but two rain gauges kept at Ilugun during the autumn of 1924 showed that the rainfall there did not differ greatly from that at Moor Plantation.

The Specific Conductivity of the Soil Extract as an Indication of Fertility.

Dr Mason and the author (2) found that there was no marked relation between the specific conductivities of the soil extracts and the yields of seed-cotton on the plots at Oyo and Ilugun; this perhaps is not surprising because the plots in question were widely separated and the damage caused by insect and fungous pests varied greatly on the different plots. But, as mentioned previously, we did find a relation between the specific conductivities of the soil extracts and the numbers of open bolls per acre. The specific conductivity is thus an indication of the potential yield, *i.e.*, the yield of cotton which would be produced in the absence of insect and fungous pests.

Through the kindness of Mr C. J. Lewin, Senior Botanist, who is breeding an improved variety of Ishan cotton, soil samples were taken in January 1926 from 11 rows under strain *B* and 11 rows under strain *D*. The soil on these rows was very variable as shown by the yields of maize which was planted before the cotton, and also by the specific conductivities of the soil extracts, which varied from 10 to 24×10^{-6} mhos. The rows were 6 ft. apart, and it is probable that under these conditions the damage by insect and fungous pests would be nearly the same on all the rows.

A graph of conductivity measurements and mean yields of lint per plant per row showed that a relationship existed, although the variations of individual points from any mean curve that could be drawn were considerable. However, remembering that the yield of lint cannot increase indefinitely, but must approach a maximum, it appears justifiable to assume that the relationship between yield and conductivity would in the absence of other factors be expressed by an equation of

the type, $W = aK^b$, where W = the mean yield of lint per plant per row (in grams) and K = the specific conductivity of the soil extract $\times 10^6$. In the case in question the equations were

$$W = 11{\cdot}65\, K^{0{\cdot}91} \text{ for strain } B,$$

and

$$W = 7{\cdot}84\, K^{0{\cdot}86} \text{ for strain } D.$$

On December 2 and again on December 30, 1926 samples of soil were taken from six cotton plots on the Government Farm at Ilorin, on which three kinds of cotton were growing. Plots 13, 14 and 15 are adjoining plots on one block, and plots 34, 35 and 36 are adjoining plots on another block, where the soil is slightly different. Below are given the numbers of the plots, the kind of cotton grown on each plot, the specific conductivities of the soil extracts, the numbers of bolls per acre (kindly supplied by Mr O. B. Lean) and the yields of seed-cotton (kindly supplied by Mr T. Thorton):

Plot	Kind of cotton	Sp cond. of 1 to 5 soil extract at 0° × 10⁶: 2 xii. 26	30 xii. 26	Mean	No. of bolls per acre	Yield of seed-cotton lb. per acre
13	Kabba	13	13	13	55,264	208
34	,,	20	23	22	61,840	253
14	Ilorin	15	17	16	121,984	476
35	,,	21	27	24	135,280	507
15	Ishan	14	13	14	119,488	386
36	,,	17	19	18	138,272	501

It will be seen from the above table that on each pair of plots under the same kind of cotton not only the number of bolls per acre but also the yield of seed-cotton is higher on the plot with the greater specific conductivity, thus showing that the specific conductivity is an index of the fertility of the soil.

Plot	Date of sample	Sp. cond. of soil extract × 10⁶	Decrease
1	Nov. 5, 1924	82	45
	,, 24, 1926	37	
7	,, 5, 1924	91	13
	,, 24, 1926	78	
5	Mar. 17, 1926	163	59
	,, 16, 1927	104	
7	,, 17, 1926	116	42
	,, 16, 1927	74	

The cotton plots at Ilugun were cleared from bush in the middle of 1924; after one crop of cotton was grown for experimental purposes some of them have been under continuous native cultivation since then. No data are available as to yields of crops grown by the natives; but it is well known that the fertility of soils (as measured by crop yields)

decreases under continuous cultivation. If the specific conductivity of a 1 to 5 soil extract is an index of the fertility of the soil, then a decrease would be expected when samples of soil taken at intervals of one or more years, and at the same time of the year, are compared. This has been found to be so, as shown in the preceding table.

Rates of Solution.

C. E. Millar (3) determined the rate of solution by finding the increase in the depression of the freezing point of a mixture of soil and water on standing. In this way he found that the rates of solution of virgin soils were greater than those of depleted soils; and concluded that a decrease in the rate of solution is one of the important changes a soil undergoes in passing from a virgin to a depleted condition. An attempt was made to find out if the rates of solution of the soils on the plots at Ilugun were decreasing under continuous cultivation. The rates of solution were determined by Atkins' method (1). The increase in conductivity after 7 days was determined by finding the specific conductivity of a 1 to 5 soil extract after 16 hours as described above, and then finding the conductivity after 7 days and 16 hours. For the latter determination there is required a duplicate soil extract, which should be kept at constant temperature for 7 days. Unfortunately this was not possible; the soil extracts were kept for 7 days in a fume cupboard built against an inner concrete wall where the temperature as shown by a thermograph varied very slightly during one week. The results obtained in this way are given in the following table:

		Sp. cond. of soil extracts		
Plot	Date of sample	After 16 hours	After 7 days and 16 hours	Increase after 7 days
1	Dec. 3, 1924	81	184	103
	Mar. 17, 1926	37	44	7
	Dec. 22, 1926	25	36	11
7	Dec. 3, 1924	51	196	145
	Mar. 17, 1926	116	218	102
	July 7 1926	71	156	85
	Dec. 22, 1926	67	154	87
8	Dec. 3, 1924	53	107	54
	Mar. 17, 1926	55	84	29

The above results indicate that the rate of solution of a soil decreases under continuous cultivation. The results, however, are not conclusive because the period during which samples have been taken from these plots is too short. In this connection it would be interesting to examine any soil samples that may have been taken at intervals and at known dates from unmanured plots in long time field experiments.

SUMMARY.

1. Considerable differences were found in the specific conductivities of different soils at any one time of the year, and considerable differences in any one soil at different times of the year, the specific conductivities being highest in March and lowest in June and July. Hence it is only possible to compare different soils when samples of these soils are taken at the same time of the year.

2. A relation has been found between the specific conductivities of the soil extracts and the mean weights of lint per plant per row in the case of 2 strains of Ishan cotton. Other data are presented showing that the specific conductivity of a 1 to 5 soil extract is an index of the fertility of the soil.

3. It has been found that the specific conductivity of a soil decreases under continuous cultivation. There is evidence that the rate of solution also decreases under the same condition.

REFERENCES.

(1) ATKINS, W. R. G. (1924). *Journ. Agric. Sci.* **14,** 198.

(2) MASON, T. G. and WRIGHT, C. H. (1925). *Fourth Annual Bull. Agric. Dept. Nigeria,* **3.**

(3) MILLAR, C. E. (1923). *Soil Sci.* **16,** 433.

(4) STEWART, G. R. (1918). *Journ. Agric. Research,* **12,** 311.

(5) STEWART, G. R. and MARTIN, J. C. (1921). *Ibid.* **20,** 663.

(*Received October 22nd,* 1927.)

MAIZE SILAGE. II.

By H. E. WOODMAN, Ph.D., D.Sc. and A. AMOS, M.A.
(School of Agriculture, Cambridge.)

In an earlier communication on this subject (1), the writers arrived at the conclusion that the main reason for the comparative failure of attempts to grow maize as a silage crop in this country was due in large measure to the general use of the late maturing variety, American Horse Tooth. It was predicted that success would probably depend on discovering a variety of maize which is able to reach the desirable stage of maturity under English conditions before being cut for the silo. Preliminary trials had indicated that the necessary qualities might be found in certain varieties like Saltzer's North Dakota, Longfellow, Compton's Early and White Cap, all of which mature at least a month before American Horse Tooth.

During the season of 1925, however, trials were carried out at the University Farm on a variety of maize obtained from France, known as Jaune Gros du Domaine. The results were highly promising; the variety proved not only to be very early, but also to be capable of producing a large crop. It was decided, therefore, to carry out a trial of this variety on a larger scale during 1926.

The crop was grown upon 3 acres of light thin gravel, manured with 12 loads of dung per acre. The seed was drilled on May 28 at the rate of 1 bushel per acre in 19 in. rows. Germination was quick, but just before the plants appeared above ground, the field was lightly harrowed to kill seedling weeds—an operation which was most successful. The crop was horse-hoed twice and hand-hoed once. During the latter operation, surplus plants were cut out, so as to leave the plants roughly 9 in. apart in the row.

The season suited the crop admirably, so that when cut for silage on September 27, it was 6 to 7 ft. high and weighed about 17 tons to the acre. Each plant was carrying one or two cobs of corn, the latter being at the proper stage of maturity for ensiling. The maize grains were firm and in the "glazed" condition which is considered ideal for silage in America. The crop was preserved in a commercial wooden tower silo.

The quality of the resulting silage was excellent, an opinion which was endorsed by several independent observers with American ex-

perience of maize silage. Its smell and appearance were all that could be desired, there being a complete absence of any indications of the presence of undesirable constituents like butyric acid. It was eagerly consumed by animals on the farm.

DIGESTION TRIAL ON MAIZE SILAGE.

With the object of instituting a comparison, in respect of composition and nutritive value, between maize silage as made in America and the silage resulting from the preservation of the Jaune Gros maize grown on the University Farm at Cambridge, a digestion trial was carried out with two pure-bred Suffolk wether sheep, aged about 20 months at the time of the trial in October and November, 1926. Prior to feeding, the silage was cut up in a machine fitted with revolving knives, since otherwise the presence of portions of cob rendered accurate sampling of the material for analytical purposes a matter of impossibility. The daily ration of the sheep consisted of 5000 gm. of the silage. The experimental period, during which collection and analysis of the faeces were carried out, was of 14 days' duration.

Table I. *Mean Composition of Silage and Faeces.*

	Maize silage (as fed to sheep)	Maize silage* (American)	Faeces (on basis of dry matter)	
			Sheep I	Sheep II
	%	%	%	%
Moisture	79·08	79·0	—	—
Crude protein	2·32	1·9	11·13	11·48
Ether extract	1·18†	0·6	1·90	1·99
N-free extractives	11·29	11·3	51·30	51·39
Crude fibre	4·88	5·8	22·45	21·29
Ash	1·25	1·4	13·22	13·85
True protein	1·09	—	—	—
"Amides"	1·23	—	—	—

* Mean of 53 American analyses (2). † Including organic acids of silage.

Comments on Table I. Considerable similarity is to be noted between the composition of the maize silage used in the present feeding trial and that of American maize silage, the agreement being especially noteworthy in respect of moisture and carbohydrate content. On the whole, however, the English silage displays a composition slightly superior to that indicated by the average American data, being somewhat richer in crude protein and crude oil, and somewhat poorer in fibre. Analysis of aqueous extracts of the silage showed that the free and combined non-volatile organic acids (1·38 per cent., expressed as lactic acid) were present in excess of the free and combined volatile

organic acids (0·72 per cent., expressed as acetic acid), a feature which is characteristic of well-made silage. The amount of volatile bases in the material was exceedingly small (0·09 per cent., expressed as crude protein), an indication that preservation of the crop had been effected without the occurrence of changes of a putrefactive character.

Table II. *Digestibility of Maize Silage.*

Daily ration = 5000 gm. silage.

Sheep I.

	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.
Consumed	1046·00	983·50	116·00	59·00	564·50	244·00	62·50
Voided	335·90	291·50	39·06*	6·38	172·32	75·41	44·40
Digested	710·10	692·00	76·94	52·62	392·18	168·59	18·10
Digestion coefficients (	67·89	70·36	66·32	89·19	69·48	69·10	28·96

Sheep II.

	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.
Consumed	1046·00	983·50	116·00	59·00	564·50	244·00	62·50
Voided	326·20	281·02	41·19*	6·49	167·63	69·45	45·18
Digested	719·80	702·48	74·81	52·51	396·87	174·55	17·32
Digestion coefficients (%)	68·81	71·43	64·49	89·00	70·30	71·54	27·71
Mean digestion coefficients (%)	68·4	70·9	65·4	89·1	69·9	70·3	28·3

* Calculated on nitrogen in *fresh* faeces.

Comments on Table II. This table summarises the data requisite for the calculation of the digestion coefficients in the maize silage. That the digestibility of the maize silage made from the Jaune Gros maize fodder compares favourably not only with the digestibility of American maize silage, but also with that of silage made from the oat and tare crop in this country, is apparent from the data recorded in Table III.

Table III. *Comparative Summary of Digestion Coefficients.*

	"Acid brown" (3) oat and tare silage %	"Green fruity" (4) oat and tare silage %	Maize silage (present trial) %	Maize silage* (American) %	Green maize† (American) %
Dry matter	55·3	64·1	68·4	64	68
Organic matter	55·8	65·9	70·9	—	—
Crude protein	67·2	65·1	65·4	53	66
Ether extract	78·9	73·4	89·1	71	86
N-free extractives	52·2	70·5	69·9	66	71
Crude fibre	49·7	57·1	70·3	68	65

* Mean results of 17 American trials} (2).
† ,, ,, 14 ,, ,, }

The results shown in Table III constitute a distinct encouragement to farmers in the southerly counties of this country to attempt the

cultivation of Jaune Gros maize for the purposes of ensilage. The maize silage of the present investigation displayed a higher digestibility than is indicated by the mean results of trials carried out in America, the differences in favour of the English sample being pronounced in the case of the protein and ether-soluble constituents. There is, it will be noted, very close correspondence between the digestion coefficients of the English maize silage and those obtained in American digestion trials on *green* maize. It would thus appear that the preservation of the Jaune Gros maize fodder in the silo had not had the effect of depressing digestibility to any marked extent. Indeed, the coefficient for the fibre in the silage is actually higher than that for the fibre in the green crop, though this is in agreement with the fact established in earlier Cambridge investigations that the digestibility of the fibre of a green crop is enhanced as a result of the actions which go on during storage in the silo.

It will further be noted that maize silage is much more digestible than "acid brown" oat and tare silage. Even "green fruity" oat and tare silage, a type highly prized in this country on account of its palatability and digestibility, is not so digestible as the maize silage, the fibrous constituent in the latter material being assimilated by ruminants to a much greater extent than is the fibre of the oat and tare silage. The results suggest that the maize crop, when cut for silage in late September, is not so advanced in lignification as is the oat and tare crop when cut for the same purpose in June.

Table IV. *Summary of Digestible Nutrients in Maize Silage.*

	Maize silage (79·08 % moisture) (Present investigation) %		Maize silage (79 % moisture) (American investigations) %	
Digestible crude protein	1·52		1·01	
" ether extract	1·05		0·43	
" N-free extractives	7·89	11·32	7·46	11·40
" crude fibre	3·43		3·94	
" organic matter	13·89		12·84	
Starch equivalent per 100 lb. silage*	12·10		10·80	
" " dry matter	57·90		51·50	
Nutritive ratio	9·00		12·30	

* V = 82 % (*Rations for Live-stock*, T. B. Wood).

Comments on Table IV. The results recorded in this table further emphasize the very satisfactory nutritive properties of the silage made from the Jaune Gros maize crop. In respect of total digestible carbohydrate (fibre + N-free extractives) the English and American figures show remarkably close agreement; on the other hand, however, the

English sample was richer in respect of digestible protein and was therefore characterised by a rather narrower nutritive ratio. The starch equivalent of 100 lb. of the dry matter of the silage amounted to 57·9, a value which must be regarded as high, when it is compared with the corresponding figure of 45·6 for "green fruity" oat and tare silage.

Feeding Trial with Calves on Maize Silage.

With the object of securing a further measure of the nutritive value of the maize silage, a feeding trial with 12 calves was carried out on the University Farm at Cambridge. The animals were divided into two groups, both groups at the beginning of the trial receiving a basal ration consisting of 6 lb. of good meadow hay together with 4 lb. of a mixture composed of equal parts by weight of linseed cake, bean meal and crushed oats. In addition, the first group received 14 lb. of maize silage per head per day, while the animals in the second group were given 14 lb. of kohl rabi and 1 lb. of oat straw chaff. The rations conformed to the requirements of cattle of about 3½ cwt. live-weight. Frequent dry matter determinations were made on the silage and roots, and as these varied during the course of the trial, the rations were adjusted accordingly. Table V shows the amounts of dry matter, digestible protein and starch equivalent in the rations during the first stage of the trial. The data for the maize silage are calculated on the basis of the results of the present digestion trial, while for the other components of the rations, the average values from Prof. T. B. Wood's *Rations for Live-stock* have been assumed.

Table V. *Nutritive Value of Experimental Rations.*

Silage Ration.

	Dry matter lb.	Digestible protein lb.	Starch equivalent lb.
Basal ration	8·70	1·03	4·88
Maize silage	2·90	0·21	1·69
Total ration	11·60	1·24	6·57

Kohl Rabi Ration.

	Dry matter lb.	Digestible protein lb.	Starch equivalent lb.
Basal ration	8·70	1·03	4·88
Kohl rabi	1·80	0·10	1·16
Oat straw chaff	0·90	0·01	0·17
Total ration	11·40	1·14	6·21

As the cattle increased in weight, and their appetites in like manner, the weight of silage was increased, first to 17½ lb. and finally to 21 lb., the roots and oat straw being increased in like proportion. A first period of feeding from November 18 to January 21 was succeeded by a second period from January 27 to April 8, in which the silage-fed

animals of the first period were given roots and oat straw, and *vice versa*. By this means, a fairer comparison of the two rations was made possible. The average live-weight increases were as follows:

		Silage-fed lb.	Roots-fed lb.
First period (9 weeks).	Average increase	122½	123½
Second period (10 weeks).	" "	136	126

The data in connection with the cattle feeding trial afford a very interesting confirmation of the results of the digestion trial. It would be anticipated from the figures given in Table V (in which the maize silage values are calculated on the basis of the results of the digestion trial) that slightly better live-weight gains would be obtained with the ration containing silage than with that containing roots. That this was actually found to be the case is evidence of the reliability of the conclusions drawn from the results of the digestion trial.

CONCLUSIONS.

It has been demonstrated that the French variety of maize known as Jaune Gros du Domaine possesses all the characteristics essential to its success as a silage crop in the southerly counties of this country. Not only is it able to grow satisfactorily during an English season to the stage of maturity desirable for maize ensilage, but it also yields a heavy weight of green matter per acre. When preserved in a tower silo, it gives rise to silage of the type and quality ordinarily obtained in America.

In respect of composition, digestibility and nutritive value, the silage obtained in the present investigation from Jaune Gros maize fodder was somewhat superior to American maize silage, taking the average results of numerous investigations in that country for the purposes of the comparison. Compared on the dry matter basis, its nutritive value was also superior to that of "green fruity" oat and tare silage.

Further feeding trials on calves confirmed the results of the digestion trial in respect of the feeding value of the Jaune Gros maize silage.

REFERENCES.

(1) WOODMAN and AMOS (1924). *Journ. Agric. Sci.* **14**, 461.
(2) HENRY and MORRISON (1917). *Feeds and Feeding.* 17th Edition.
(3) WOOD and WOODMAN (1921). *Journ. Agric. Sci.* **11**, 304.
(4) WOODMAN (1922). *Ibid.* **12**, 144.

(*Received October 28th*, 1927.)

THE MECHANICAL ANALYSIS OF HEAVY FERRUGINOUS SOILS.

By RUBY C. GROVES, M.Sc., A.I.C.

(*Mineral Resources Department, Imperial Institute, South Kensington, London, S.W. 7.*)

The deflocculation of heavy ferruginous soils prior to their physical examination has presented difficulties to many workers and on this account it has been considered likely that the experience gained in the laboratories of the Imperial Institute may be useful to many who have to deal with similar soils, particularly those of tropical origin.

The sub-committee appointed by the Agricultural Education Association (1), in the course of their recent investigations into the question of the mechanical analysis of soils, state that the preliminary dispersive treatment recommended by them for ordinary soils is not satisfactory with some ferruginous soils. A similar difficulty has been experienced at the Imperial Institute, where it has hitherto been customary to carry out mechanical analyses of soils by means of a Schöne-Mayer elutriator, after subjecting the soil to a preliminary treatment consisting of boiling it with 0·5 per cent. solution of ammonia, followed by gentle trituration with a rubber pestle for one-half to one hour. This treatment has been successful on the whole, but it has been found ineffective in the case of heavy ferruginous soils, owing partly to the difficulty of securing a proper dispersion of the clay and partly to the ease with which the dispersed clay is reflocculated.

During the course of an investigation on the possibility of substituting for the elutriator method the "pipette method" of Robinson (2), it was found that the preliminary treatment of the soil with hydrogen peroxide in order to destroy or render soluble the humic matter which may act as a cementing agent on the clay particles (3), did not give a satisfactory dispersion of the clay in the case of heavy ferruginous soils. This conclusion is in agreement with the observations of the Agricultural Education Association sub-committee on this matter.

As it was desirable, in changing from the elutriator to the pipette method, to make the use of the latter applicable to all types of soil, an attempt was made to modify the peroxide treatment so that it should effectively deflocculate this type of soil, which is fairly common in tropical and sub-tropical localities.

It may be here mentioned that the Sudan method recommended by Joseph and Martin (4), in which the soil is dispersed directly with sodium carbonate, was also tried, but was found to be ineffective with these ferruginous soils.

MODIFICATIONS OF THE PEROXIDE TREATMENT.

Various modifications of the peroxide treatment were then tried. The soil used for these experiments was a heavy clay, containing 26·55 per cent. of iron oxide (Fe_2O_3) soluble in hydrochloric acid, and a fairly large amount of organic matter, and having a strongly acid reaction. As determined by means of the Schöne elutriator, with previous repeated treatment with a 1 per cent. solution of caustic soda, the sample contained over 70 per cent. of fine silt and clay. Treatment with hydrogen peroxide, on the lines recommended by Robinson, did not effect complete dispersion of the soil, the sand fraction so obtained consisting largely of coagulated smaller particles. It was observed, however, that this "sand" fraction readily yielded further quantities of clay on stirring or gently rubbing with a rubber pestle, and that this breaking down process was very much hastened by the addition of a few drops of ammonia. Further portions of the sample were therefore submitted to the action of hydrogen peroxide to which a small quantity of ammonia had been added. In some cases the soil was also gently rubbed with a rubber pestle until no more clay separated, both with and without mechanical shaking. The combined action of the ammoniacal peroxide and the gentle rubbing gave a much better dispersion of the soil than could be obtained by the other methods. In all cases the second stage of the treatment (dilute hydrochloric acid, followed by filtration and dispersion in ammoniacal water) was the same.

The silt, fine silt and clay fractions were determined by the pipette method (2). The total sand was determined by the 10 cm.-100 seconds sedimentation (5), but as the amount of true sand was known to be small and the investigation was chiefly concerned with the clay fraction the sand was not separated into fine and coarse fractions.

The several preliminary treatments to which the soil was subjected before mechanical analysis were as follows:

(1) Neutral peroxide, without rubbing or shaking.
(2) Neutral peroxide, with rubbing but no shaking.
(3) Ammoniacal peroxide, without rubbing or mechanical shaking.
(4) Ammoniacal peroxide, with 24 hours mechanical shaking but without rubbing.

(5) Ammoniacal peroxide, with rubbing but without mechanical shaking (for details see p. 204).

(6) Ammoniacal peroxide, with rubbing and 24 hours mechanical shaking.

In the following table are shown the results of the mechanical separation of the soil treated by the above six methods—in all cases the results are reported on fractions dried at 105° C.:

Table I.

Treatment No.	1	2	3	4	5	6
	Percentage of 1 mm. fine earth, expressed on air-dry material					
Sand...	20·43	4·21	17·71	12·81	2·71	2·29
Silt	12·55	14·55	12·17	12·45	10·20	11·23
Fine silt	29·95	45·78	34·73	40·62	48·20	48·52
Clay	21·73	21·50	21·05	20·73	25·40	24·83
Calcium carbonate	Nil	—	—	—	—	—
Loss by solution in dilute HCl ...	2·03	—	—	0·76	0·99	1·00
Organic matter dissolved by H_2O_2	—	—	—	—	5·31	—
Water-soluble matter	0·03	—	—	—	—	—
Moisture at 105° C.	6·01	—	—	—	—	—

In this soil, the mineral matter dissolved by the hydrogen peroxide and hydrochloric acid treatment was observed to include a fairly high proportion of manganese, in addition to silica, alumina, and ferric oxide. The manganese oxide was, in all cases, precipitated with the silica and sesquioxides by adding a few drops of bromine before the addition of ammonia.

It will be observed that the loss on solution in HCl is higher after treatment with neutral peroxide than after the ammoniacal peroxide. This is probably due to the more complete flocculation of the clay which takes place on adding acid to the solution after the ammonia treatment.

Organic Matter dissolved by Hydrogen Peroxide.

The Agricultural Education Association (1) recommend that all fractions should be expressed on an ignited basis and therefore loss on ignition is included in the totals for mechanical analysis, but this procedure has not been adopted at the Imperial Institute owing to the error caused, particularly in the clay determination, by the expulsion of combined water. It becomes necessary therefore to determine the amount of organic matter dissolved or destroyed by the hydrogen peroxide treatment. According to G. W. Robinson and J. O. Jones (6) only the humus is attacked by the peroxide, and hence the figure

obtained for "humus" by treatment of the soil with ammonia in the usual way might be used. However, W. O. Robinson (7) has recently shown that in the presence of soil, organic matter other than humus is attacked by peroxide. A direct determination of the organic matter dissolved or destroyed by the peroxide treatment was therefore made by submitting a small portion of the soil to exactly the same treatment as was received by the main portion, filtering through a very compact pad of asbestos in a Gooch crucible, drying at 105° C. and determining the loss in weight. This loss, minus moisture determined at 105° C., represents the organic matter destroyed by peroxide treatment. The filtrate was evaporated to dryness, ignited, and the residue weighed and its weight deducted from that of the organic matter destroyed. This method was tried on a number of soils and gave consistent results which were in all cases higher than the figure obtained for humus by solution in ammonia. It is recognised that the peroxide treatment, especially in the presence of ammonia, may cause the solution of a certain amount of mineral matter, which would be included in the figure for "loss by solution in HCl" in the ordinary course of analysis. As to whether this small quantity of mineral matter is actually dissolved as such by the peroxide treatment, or whether it consists wholly or partly of mineral "ash" combined with the organic matter, is a matter of doubt (cf. W. O. Robinson, *loc. cit.*). Joseph and Whitfeild (8) in preparing specially purified samples of humus for use in a colorimetric method of determination, state that they found it impossible to remove all the inorganic material from the humus, even by treatment with hydrochloric and hydrofluoric acids.

USE OF AMMONIACAL PEROXIDE COMBINED WITH TRITURATION.

It is evident from the results quoted in Table I that of the several methods of treatment tried, the most effective for giving a proper dispersion of this soil is that involving the use of ammoniacal peroxide combined with gentle rubbing. The combination of neutral peroxide with rubbing gives a much better dispersion than is effected by the action of neutral peroxide alone, as also does the use of ammoniacal peroxide. Ammoniacal peroxide without rubbing but with 24 hours mechanical shaking is rather more effective than ammoniacal peroxide without either rubbing or shaking, but not so good as neutral peroxide combined with rubbing.

The treatment involving the use of ammoniacal peroxide and gentle rubbing is the most effective and the dispersion obtained by such

treatment is not increased by mechanical shaking for 24 hours. The concentration of ammonia used is very low so that it would not be likely to have much more solvent effect on the unweathered mineral particles than would neutral peroxide. In fact, as already pointed out, it will be seen from Table I that the mineral matter dissolved by hydrochloric acid after ammoniacal peroxide treatment is lower than after neutral peroxide.

It should be noted that trituration of the soil sample is a recognised and widely used treatment and is mentioned by Novák(9) in a list of methods for comparative analyses of soils after various methods of preparation.

On the basis of the results recorded above (which can be readily duplicated) the conclusion has been reached that treatment with ammoniacal peroxide combined with rubbing provides a means of obtaining a more satisfactory dispersion of this type of soil than can be obtained by other means and mechanical shaking is not necessary.

Method Recommended.

The following details of the method employed may be of interest:

20 gm. of the 1 mm. fine earth are weighed into a large porcelain evaporating basin (at least 6 in. in diameter), placed on a water-bath, or over a rose burner, the soil is just moistened with water, a few drops (4 to 6) of 50 per cent. ammonia are added, and 20 c.c. of 6 per cent. hydrogen peroxide. The reaction between the peroxide and the organic matter in the soil is rendered more vigorous by the presence of the ammonia, so that considerable care is necessary to prevent loss of the mixture by frothing. When the first reaction has subsided, the additions of ammonia (2 or 3 drops) and hydrogen peroxide (not more than 20 c.c. at a time) are repeated so long as any evolution of gas occurs. Any solid particles left by the frothing above the level of the liquid are washed down with a little hot water. When the action of the ammoniacal peroxide has ceased, the dish is allowed to cool. (It is useful, though by no means essential, to allow the dish to remain on the water-bath until its contents are evaporated to a paste.) When all the peroxide has been destroyed the residual soil is gently but thoroughly rubbed with a rubber pestle, 2 or 3 drops of ammonia being added. Only a very light pressure should be exerted on the pestle.

The volume of the solution is next made up to 100 c.c. by the addition of cold water. The contents of the dish are thoroughly stirred, allowed to stand for a few seconds, and the suspended matter poured off into a large (2-litre) beaker. About 50 c.c. of cold water are added

to the dish, the contents stirred, and the decantation of the suspended matter repeated. The residue in the dish is again gently triturated with the rubber pestle in the presence of a few drops of ammonia. This process is repeated so long as any clay is separated. It is necessary, especially during the early stages when the suspension is very turbid, to exercise great care during decantation so that only actually suspended matter is poured off. The end point, which is quite definite, is taken as being reached when no more clay is separated by gentle rubbing for 2 or 3 minutes. When no more clay can be obtained the remaining contents of the dish are transferred to the beaker and sufficient normal hydrochloric acid is added to give a concentration of about $N/5$, allowance being first made for any acid required to neutralise the ammonia present. After standing for about an hour with frequent stirring, the mixture is filtered and washed as usual. The mechanical shaking may be omitted, in which case the residue on the filter may be washed directly into the 1000 c.c. graduated cylinder, 50 c.c. of 10 per cent. ammonia added, and after thorough shaking by hand, the fractions may be determined according to the usual technique of the pipette method.

SUMMARY.

Certain heavy ferruginous soils do not respond to the usual preliminary treatment with hydrogen peroxide for mechanical analysis by the pipette method.

A method of preliminary treatment is described, involving the use of ammoniacal hydrogen peroxide and repeated gentle rubbing with a rubber pestle which appears to give a satisfactory dispersion with such soils.

The results are not affected by mechanical shaking, which may therefore be omitted.

REFERENCES.

(1) Agric. Educ. Assoc. Sub-committee (1926). *Journ. Agric. Sci.* **16**, 123.
(2) ROBINSON, G. W. (1922). *Ibid.* **12**, 306.
(3) —— (1922). *Ibid.* **12**, 287.
(4) JOSEPH, A. F. and MARTIN, F. J. (1921). *Ibid.* **11**, 293.
(5) Mechanical Analysis of Soils (1905–6). *Ibid.* **1**, 470.
(6) ROBINSON, G. W. and JONES, J. O. (1925). *Ibid.* **15**, 26.
(7) ROBINSON, W. O. (1927). *Journ. Agric. Research*, **34**, 339.
(8) JOSEPH, A. F. and WHITFEILD, B. W. (1927). *Journ. Agric. Sci.* **17**, 1.
(9) NOVÁK, V. (1925). *Internat. Rev. Sci. and Prac. Agric.*, New Series, **3**, 460.

(*Received November 14th*, 1927.)

A SIMPLE METHOD FOR THE DETERMINATION OF THE pH VALUES OF TURBID SOIL AND OTHER SOLUTIONS.

By C. H. GADD, D.Sc. (Birm.)
(*Mycologist, Tea Research Institute of Ceylon.*)

In the course of investigations into the cause of an obscure pathological condition of the tea bush, it became necessary to make pH determinations of certain soils. Electrometric apparatus and a suitable centrifuge for clearing the solutions were not available. Considerable difficulty was experienced in making the determinations with accuracy by indicator methods owing to two causes. First, the turbidity of the soil solutions made comparison with standard buffer solutions somewhat difficult; secondly, the colours developed in the soil and buffer solutions with some indicators were different in hue, as distinct from shade or tint. This rendered exact matching quite impossible. The latter difficulties also arose when the drop ratio method was used instead of standard buffer solutions. The errors resulting from these causes were believed to be unduly large, and it was felt that greater accuracy would be attained if these difficulties could be overcome.

It is well known that filtration of a soil solution through filter paper results in an alteration of the hydrogen-ion concentration of the solution. The error due to filtration was found to be more than 0·5 in the pH scale with some soils, even when the first 25 c.c. of the filtrate was discarded. It was evident, therefore, that filtration would not solve the difficulty, because it introduces another cause of error. A standard correction for filtration could not be applied, as the variation in the hydrogen-ion concentration of different soil solutions due to this cause was not constant.

Ultimately, the difficulties were overcome by the adoption of a very simple method which, it is hoped, may be of use to other workers labouring under similar disadvantages. The basic principle underlying the method has already been used by Atkins (1) for the determination of the pH values of plant juices by the "drop method," and the writer would here make due acknowledgment to him.

The soil solution is prepared, as usual, by shaking the soil vigorously with distilled water. The writer used two parts of water to one of air

dry soil, and the shaking was carried on for ten minutes. The vessel is then allowed to stand for 24 hours in order that the larger and some of the finer particles may settle.

Having decided by rough tests what indicator is best to use, a sufficient quantity of the indicator is added to a sample of the soil solution to make the colour clearly visible in the turbid fluid. About 3 c.c. of the indicator solutions recommended by Clark (2) are required for 25 c.c. of the soil solution; if the latter is very turbid, the amount of indicator may be increased to double that amount. The exact quantity is immaterial. Equal quantities (about 5 c.c.) of this coloured sample are then placed in standard comparator tubes or other suitable tubes of uniform bore.

Ten drops of distilled water are added to one of these tubes. This tube is used as a control. Ten drops of buffer solution of known *p*H value are then added to another tube and the resulting colour is compared with that of the control tube. If no alteration in colour occurs, the soil solution and the buffer have the same *p*H value. If an alteration in colour occurs, other buffer solutions must be tried in other tubes until one is found which causes no alteration. It may happen that one buffer solution is too acid and the next in the range too alkaline, then the *p*H of the soil may be estimated by interpolation. If, owing to excessive turbidity of the soil solution it is difficult to ascertain which buffer solution has caused the least alteration in colour, the control and the two buffered tubes in question may be diluted with equal quantities of distilled water and again compared. The amount of water added is immaterial so long as equal amounts are added to each tube; but the minimum to determine the point should be added.

It will be realised that the quantities of soil solution, indicator and buffer solutions given above are quite arbitrary. Larger or smaller quantities may be used as found necessary, but it is advisable to reduce to a minimum the amount of buffer solution used.

It may be of interest to record that the writer has found Brom cresol purple to be quite useless with some soil solutions. This, however, does not appear to be a common experience, so possibly the particular sample of indicator used was at fault. The solution was made according to the directions given by Clark. The correct colour was developed when buffer and certain other solutions were used, but with many soil solutions the yellow (acid) colour developed even when the *p*H of the solution was known to be greater than 6·0, as shown by methyl red, chrom phenol red and brom thymol blue.

The method of determining the hydrogen-ion concentration of turbid solutions here described has several advantages which tend towards greater accuracy. The colour of the turbid solution is viewed through one tube only. The same colour is present in the solutions to be compared. The criterion is an alteration in colour, which for some people is probably easier than colour matching. Lastly, the solution need not be greatly diluted. Dilution, as a rule, is quite unnecessary except for a final check.

REFERENCES.

(1) ATKINS, W. R. G. (1925). "The hydrogen-ion concentration of plant cells." *Notes from the Bot. School, Trinity College, Dublin*, **3**, 178–190.

(2) CLARK, W. M. (1925). *The determination of hydrogen-ions*, Baltimore.

(*Received November 23rd*, 1927.)

THE VARIATIONS IN MILK YIELDS CAUSED BY SEASON OF THE YEAR, SERVICE, AGE, AND DRY PERIOD, AND THEIR ELIMINATION.

PART IV. DRY PERIOD, AND STANDARDISATION OF YIELDS.

By H. G. SANDERS, M.A.

(Institute of Animal Nutrition, School of Agriculture, Cambridge.)

(With Eleven Text-figures.)

Section A. The Effect of the Length of the D.P. on the Total Lactation Yield.

Of the 3918 lactations dealt with in this investigation, 879 were of 1st calvers, and the length of the preceding D.P. was known in 2713 cases, leaving 326 in which it could not be ascertained; the distribution of the known D.P.'s has been discussed in Part I, and it has been noted that the mean D.P. is short before the 2nd lactation.

In Part I a partial correlation of + 0·308 was found, between the length of the lactation and the length of the preceding D.P., when Service Period and Age were held constant, but this was not interpreted as being a physiological relationship, but as a measure of individuality, as showing the probability that a cow that has been dry for a long time before calving, will again dry off early.

A correlation table was drawn up, between the length of the D.P. and the yield in the next lactation, but is not given, as in the writer's opinion it is quite meaningless; there was no relation apparent, except that, following D.P.'s of over 100 days, the mean yields were definitely lower—*i.e.* only the worst cows, on the average, were dry for so long.

In view of the tendency for high yielding cows to have short rests and *vice versa*, it is quite clear that this effect can only be measured by comparing the yields of particular cows after varying lengths of D.P.; all lactations were corrected for Month of Calving, S.P., and Age, and two methods of testing the individual variation in yield against the D.P. were adopted.

1st Method.

There is, of course, no D.P. associated with the 1st lactation, and consequently in this method the 1st lactation has been taken as a sort

of fixed point. The numbers (all breeds) of cases in which this lactation and others were included, were as follows:

Lactations known	No. of cows	No. of lactations for which the D.P. was known
1–7	2	12
1–6	1	5
1–5	15	60
1–4	66	198
1–3	106	212
1–2	239	239
Total	429	726

The difference of each subsequent corrected lactation yield of these cows, from their 1st lactation corrected yield, was expressed as ± a percentage of the latter; to take an actual example, one cow gave corrected yields of 8244 lb., 8027 lb., 9639 lb. and 7595 lb., in her first 4 milking periods, the D.P. before the 2nd lactation being 59 days, before the 3rd, 80 days, and before the 4th, 48 days; the percentage deviations from the 1st lactation yield, for lactations 2, 3 and 4, are − 3, + 17 and − 9, which were then associated with D.P.'s of 59, 80 and 48 days respectively. A correlation table was then drawn up, between the length of the D.P.'s and the percentage deviations associated with them. Where two D.P.'s of the same cow fell in the same 10-day interval, the corresponding deviations were, of course, entered separately.

An early difficulty was encountered; the correlation coefficient between these 726 D.P.'s and the yield percentages was $+ 0{\cdot}324 \pm 0{\cdot}022$; taking the 2nd lactations by themselves, however, the correlation coefficient (429 observations) was $+ 0{\cdot}455 \pm 0{\cdot}026$, and for the others (297 observations) only $+ 0{\cdot}120 \pm 0{\cdot}039$—a difference between the results for 2nd calvers and others of $0{\cdot}335 \pm 0{\cdot}047$, which must be regarded as significant.

From the lactations included, it can be seen that a high proportion (190 in 297) of the lactations, other than 2nd calvers, were 3rd calvers.

For these 297 lactations the following rather surprising results emerged:

(*a*) Correlation between yield percentage and D.P.

$$r = + 0{\cdot}120 \pm 0{\cdot}039, \quad \eta = 0{\cdot}279 \pm 0{\cdot}036.$$

(*b*) Correlation between yield percentage and *D.P. preceding the previous lactation*

$$r = + 0{\cdot}383 \pm 0{\cdot}033, \quad \eta = 0{\cdot}497 \pm 0{\cdot}029.$$

(c) Correlation between D.P. and D.P. preceding the previous lactation

$$r = +\,0{\cdot}393 \pm 0{\cdot}033, \quad \eta = 0{\cdot}464 \pm 0{\cdot}031.$$

There is then a fairly high correlation between the two D.P.'s involved in each case, and this lessens even further the relationship (a) above; the regressions scarcely approach the linear sufficiently to justify the use of the partial correlation method, but if it is employed the coefficient (a) vanishes (the value becomes $-\,0{\cdot}033 \pm 0{\cdot}039$).

It is surprising, however, to find such a close connection between the yield and the D.P. before the previous lactation; the only possible explanation would appear to lie in the large proportion of these 297 lactations that were for 3rd calvers, and in the fact that the D.P. between the 1st and 2nd lactations has a much bigger effect than have subsequent ones.

The further conclusion follows from these results that to get really accurate corrections for D.P., the cow's whole history in this respect must be taken into account—that the D.P. has a sort of cumulative effect. In fact such was attempted, but to get any smooth and reliable results, a stupendous volume of data would be necessary; the present records did not suffice, and the attempt had to be abandoned; and here, only the immediate effect of one D.P. is dealt with, a short subsection being added, in which the existence of some kind of cumulative effect, as is suggested above, is demonstrated.

One other point seems clear, namely, that from these records of young cows, only the effect of the D.P. before the 2nd lactation can be ascertained; excluding these there was still plainly a relationship between the yield percentage and the D.P., but, with so high a proportion of the remainder being 3rd calvers, it is complicated by any "left over" effect from the D.P. before the 2nd lactation; the effect, in the case of cows older than 2nd calvers, had, therefore, to be obtained by the 2nd Method (below).

The relationship for these 429 lactations of 2nd calvers, between the percentage deviation of the yield, from the same cow's 1st lactation yield, and the length of the D.P., is shown in Fig. 36.

The means are somewhat scattered, but the fitted curve cuts through them fairly well; the equation of this curve is

$$y = 121{\cdot}0 - 44{\cdot}7\,.\,e^{-0{\cdot}01842\,.\,x}$$

where y = comparative yield when 1st lactation yield = 100,

and x = length of preceding D.P. in days.

The only mean that departs markedly from the curve is that for D.P.'s of 90–99 days, which, however, is based on only 15 observations.

In calculating corrections to allow for the effect of the length of the D.P. before the 2nd lactation, the standard is clearly chosen for us—it must obviously be taken at the point where the curve crosses the line, marked with an arrow in Fig. 36, which represents a comparative yield of 100—*i.e.* the same as the 1st lactation; if any other

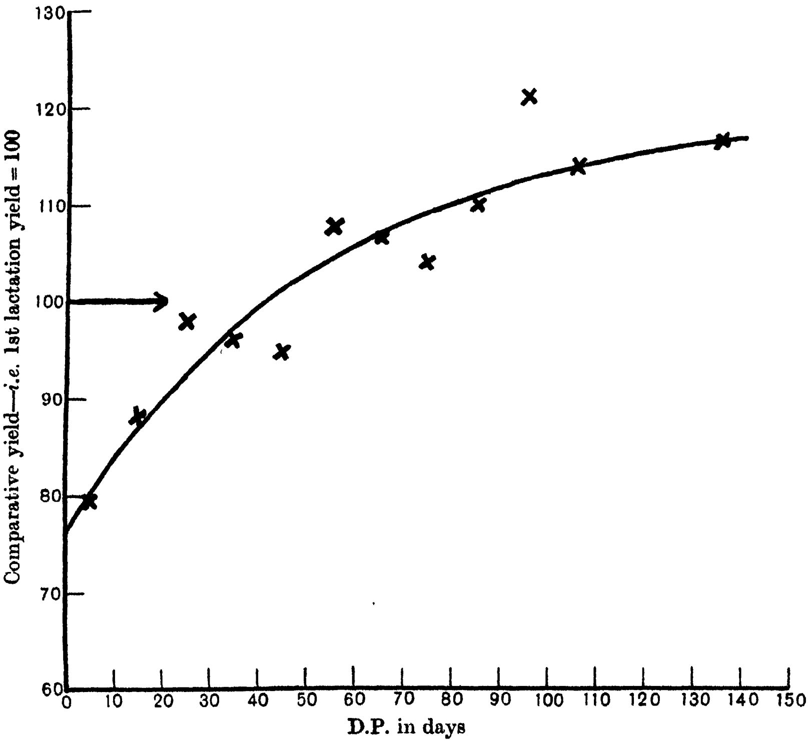


Fig. 36. Effect of the length of the preceding D.P. on the lactation yield. 2nd calvers only.

standard is taken the corrected yields of 2nd calvers will not compare with those of 1st calvers. The point given is almost exactly on the ordinate for a D.P. of 40 days; such is then the "average" D.P., in the sense that the extent to which the yields of all the cows included with a shorter one were lowered, was the same as that to which the yields of all cows with a longer one, were raised; this will not agree with the arithmetical average length of D.P., because the effect shown in Fig. 36 is not linear, a D.P. of 40 – 30 = 10 days, needing a considerably

greater positive correction, than one of $40 + 30 = 70$ days needs a negative one. From the distribution of length of D.P. we have

$$\begin{aligned} \text{Mean} &= 54{\cdot}4 \text{ days} \\ \text{Median} &= 45{\cdot}6 \quad ,, \\ \text{Mode} &= 28{\cdot}0 \quad ,, \end{aligned}$$

so that 40 days lies between the Median and the Mode, and consequently is quite a normal length to take as a standard.

Table XXVII gives the percentage corrections, obtained as before, for different lengths of D.P., for 2nd calvers; it is surprising to note that for a cow dry for less than 10 days before the 2nd lactation, as much as 25 per cent. must be added on to the yield to compensate for the milk lost, and 15 per cent. must be taken off for very long D.P.'s; this is discussed further, below (p. 222).

Table XXVII. *Corrections for Length of D.P.—2nd Calvers only. Standard = 40 days.*

Length of D.P. (days)	Comparative yield given by curve (1st lactation yield = 100)	Corrections for D.P. %
0–9	79·9	+25·1
10–19	86·8	15·2
20–29	92·6	8·0
30–39	97·3	2·8
40–49	101·3	−1·3
50–59	104·6	4·4
60–69	107·4	6·4
70–79	109·7	8·8
80–89	111·6	10·4
90–99	113·2	11·7
100–109	114·5	12·7
110–119	115·6	13·5
120 and over	117·3	14·7

Breeds. Before the effect of the length of the D.P. on the yield of older cows is described, breeds, and high and low yielders are treated. To find this variation accurately a very great number of records is necessary, for some have to be omitted because the D.P.'s are unknown, and individual comparisons must be made; it will be realised that the data contained single lactations of many cows and these were no use for the present purpose. Under these circumstances the search for differences as regards breeds and different grades of cows, was not a very exhaustive one, but a presumption was created that no such differences exist.

It was impossible to take only 2nd lactations for this breed comparison, owing to the small numbers involved, and consequently all

lactations of cows, whose 1st lactations were known, were included. The mean comparative yields (1st lactation yield = 100) for the various 10-day intervals of D.P. for the different breeds are given in Table XXVIII; the figures obtained by taking all lactations of all cows in the same way are also shown, and it will be seen that no smoothing has been done.

Table XXVIII. *Comparative Yield (1st Lactation 100) after different lengths of D.P.*

D.P. (days)	Comparative yield: Mongrels	Red Polls	Lincoln Reds	Friesians	All Cows
0–9	82·7	75·8	82·5	77·5	80·1 ± 1·5
10–19	92·3	83·3	90·9	92·5	90·5 ± 1·5
20–29	100·7	109·2	100·6	81·3	98·4 ± 1·5
30–39	97·5	97·5	105·2	90·0	99·4 ± 1·4
40–49	94·1	93·6	97·5	115·8	98·6 ± 1·6
50–59	102·6	108·3	100·7	105·0	106·5 ± 2·0
60–69	110·2	95·5	116·7	113·5	111·7 ± 2·5
70–79	109·0	115·8	108·8	128·7	111·0 ± 2·1
80–89	107·9	—	112·8	98·2	109·4 ± 2·0
90–99	121·6	88·5	114·5	120·0	113·4 ± 2·8
100–109	95·5	105·8	108·7	192·5	111·0 ± 4·1
110–119	97·5	112·5	107·5	117·5	103·2 ± 3·6
120 and over	123·8	89·4	106·0	105·8	111·4 ± 3·2
Total number	309	103	133	66	726
Correlation coefficient	+0·324 ± 0·034	+0·216 ± 0·063	+0·208 ± 0·056	+0·412 ± 0·069	+0·324 ± 0·022
Mean percentage deviation from 1st lactation yield	0·7 ± 1·0 %	−6·8 ± 1·5 %	+6·2 ± 1·2 %	+1·8 ± 2·8 %	+1·4 ± 0·6 %

The small numbers lead to considerable irregularity in the results, but it appears that the effect is roughly the same in each case. Mongrels give a fairly smooth set of figures with one or two exceptions; Red Polls agree well with the others in the first two intervals, but after that are very irregular, with an apparent tendency to less rise for the longer D.P.'s; Lincoln Reds with two exceptions (30–39 days and 40–49 days) conform very well to the average; Friesians give very irregular figures after the first 7 intervals, but up to that point agree well considering the very small number.

There is some variation in the correlation coefficients, but this may well be due to chance; thus the extreme difference is between Lincoln Reds and Friesians, and this is 0·204 ± 0·089, which is only a little over twice its probable error, and hence insignificant. The mean deviations of all observations at the foot of the table are insignificant for Mongrels, Friesians and All Cows, but that for Red Polls is definitely negative, that for Lincoln Reds definitely positive; this it will be realised was because the D.P. is significantly below normal in length for the former and above normal for the latter (Part I).

It can only be admitted that this search for breed differences was unsatisfactory, but it is believed that it was the best that could be done under the circumstances; it has however sufficed to show that this effect exists, and to suggest that it is roughly the same, in each case; there seems no reason to suppose that it should vary from breed to breed, and, although not definitely proved, the tentative conclusion must be drawn that it does not do so.

Before leaving Table XXVII one other point must be touched on—the comparison of these results with those from the Penrith data; in that case the difference in this respect, between 2nd calvers and others, was not realised and so all lactations were included together (*i.e.* as in this table); furthermore the data, being more limited, gave irregular means, and they had to be averaged in 40-day intervals—0–39, 40–79 and 80–119 days. Below is given the mean deviation (weighted) shown by the last column of Table XXVIII for the same three 40-day periods, together with the corresponding Penrith figures.

D.P. (days)	Mean deviation from 1st lactation yield %	Corresponding Penrith figures %
0–39	−6·7	−6·3
40–79	+6·6	+3·9
80–119	+9·7	+7·0

It was realised when the Penrith results were reported, that they should not be regarded as final, for, to represent this function, a curve had to be fitted to three points only; remembering this the agreement between the above figures is satisfactory; in the present case there is rather more increase in yield associated with the longer D.P.'s, and the conclusion seems inevitable that the Penrith results lost some accuracy because of paucity of data.

High and Low Yielders. We have seen that the data included 429 cows of which the 1st lactation, and one or more subsequent ones, were known; the corrected yields in all known lactations of these cows were averaged and they were then split up into two equal groups according to the figure reached; the point of division was found to be 7500 lb.—all giving a mean corrected yield in all known lactations of more than this were, therefore, taken as high yielders, and all giving a lower figure as low yielders. Table XXIX gives the mean comparative yields (1st lactation = 100) of these two groups for varying lengths of D.P.; in the last two columns the weighted means for intervals of 20-days of D.P. are shown.

Considering the irregularities, the two sets agree fairly closely; for

D.P.'s up to 100 days the divergences between the "20-day" means are very slight and roughly balance each other; after that the low yielders give two means that fit well into their places, but the high yielders do not; there seems no doubt, however, that these two are chance variations, as they are based on only 8 and 13 observations respectively.

Table XXIX. *Comparative Yield* (1*st Lactation* = 100) *after varying lengths of D.P.—High and Low Yielders.*

D.P. (days)	Comparative yield: High Yielders	Comparative yield: Low Yielders	"20-day" mean (weighted): High Yielders	"20-day" mean (weighted): Low Yielders
0–9	79·6	78·1	86·4	82·3
10–19	92·5	84·8		
20–29	100·7	96·4	98·7	98·9
30–39	98·0	102·0		
40–49	98·4	97·9	101·1	102·1
50–59	104·6	107·6		
60–69	108·0	113·9	106·2	114·3
70–79	104·4	114·7		
80–89	108·7	109·9	113·2	109·9
90–99	121·0	110·0		
100–109	101·3	113·7	99·1	111·4
110–119	96·9	107·5		
120 and over	100·2	118·5	100·2	118·5
No. of observations	366	360		
Correlation coefficient	$+0·265 \pm 0·033$	$+0·327 \pm 0·032$		
Mean percentage deviation from 1st lactation yield	$-1·7 \pm 0·8$ %	$+4·1 \pm 1·0$ %		

Low yielders give rather a higher correlation coefficient but clearly the difference from high yielders ($0·062 \pm 0·046$) is insignificant. The difference between the mean deviations is principally accounted for by the fact that high yielders have a lower mean length of D.P.; from the distribution of the actual D.P.'s included the expected deviations would be $-$ 1·4 per cent. and + 3·3 per cent. respectively—*i.e.* this explains nearly all the difference. This is of some interest as bearing out the conclusion reached in the last Part (from few cows) that, at least in the early lactations, the age variation is the same for all grades of cows; if low yielders increased to a considerably greater extent with age, it would mean that the 1st lactation yield was not raised sufficiently by correction, and we should expect to find here a markedly positive mean deviation for low yielders, and a markedly negative one for high yielders; that, when the length of D.P. is allowed for, the indication of this is so trivial affords a strong indication that in early life (*i.e.* the lactations included here) the age variation is almost exactly the same, in proportion, for high and low yielders.

Table XXIX suggests that the effect of the length of the D.P. is the same for both groups; it might have been supposed, that, if there was any variation, it would be found to be greater with high producers; no evidence at all of this is apparent—if anything the figures show rather greater rise for low yielders, but the only possible conclusion is that no difference has been found.

2nd Method.

So far, in this Section, we have only considered those cows of which the 1st lactation was known; the data, however, contained a large number of records of cows in which it was not known, and consequently some method had to be evolved by which these latter could be included. Further it has been possible, up to this point, to measure only the effect for 2nd calvers, and we have yet to find it for older cows; since there is plainly a "carry over" effect from the D.P. before the 2nd lactation, which influences the 3rd at least, all the cows included in the 1st Method were discarded here; this gives a more severe test to the data as no record is included in both the results obtained by the two methods.

Each lactation yield was first corrected, as before, for Month of Calving, Service Period and Age, and the D.P.'s were then divided into 20-day groups—0–19 days, 20–39 days, etc.—all over 120 days being put in one group; the method then was to compare the yield of each cow after a D.P. falling in one of these groups, with her yield in another lactation after one falling in a different group. When an individual had two D.P.'s falling in the same 20-day interval, they were, in this case, averaged, and treated as one; some cows with two or more known lactations had all their D.P.'s in the same interval—these had to be omitted, as, of course, had all cows with only one known lactation.

The resulting means obtained in these comparisons are shown in Table XXX, the probable errors of the means being given, where the observations numbered 20 or more; an example will make the table clear. There were 76 cows which had a D.P. lying in the 0–19 day group, and another in the group 20–39 days; after the shorter D.P. these cows gave an average lactation yield of 8158 lb., and after the longer D.P. one of 8625 lb. Thus, in the first two columns are given the means for all the comparisons with D.P.'s of 0–19 days, in the next two the remaining ones with D.P.'s of 20–39 days, and so on.

Though the actual differences may be insignificant, it will be seen that in every comparison there is a higher mean following the longer D.P., with one exception—that between 60–79 and 80–99 days, when

Table XXX. *Comparison of Mean Lactation Yields (lb.) of the same Cows after Different D.P.'s.*

	Comparisons with D.P. = 0–19 days		Comparisons with D.P. = 20–39 days		Comparisons with D.P. = 40–59 days		Comparisons with D.P. = 60–79 days		Comparisons with D.P. = 80–99 days		Comparisons with D.P. = 100–119 days		
	Mean lactation yields after												From comparison with D.P. = 0–19 days (100) only—comparative yields following D.P. on left
Days	D.P. = 0–19 days	D.P. on left	D.P. = 20–39 days	D.P. on left	D.P. = 40–59 days	D.P. on left	D.P. = 60–79 days	D.P. on left	D.P. = 80–99 days	D.P. on left	D.P. = 100–119 days	D.P. on left	
20–39	8158 ±165	8625 ±168	—	—	—	—	—	—	—	—	—	—	105·7
40–59	7574 ±243	8764 ±222	8156 ±133	8377 ±138	—	—	—	—	—	—	—	—	115·7
60–79	7885 ±281	9173 ±297	8107 ±165	8545 ±148	7630 ±150	8176 ±159	—	—	—	—	—	—	116·4
80–99	6897	8544	7438 ±156	7982 ±183	7868 ±158	8294 ±175	7880 ±133	7750 ±157	—	—	—	—	123·9
100–119	7000	9062	7500 ±297	8117 ±224	7500 ±232	7977 ±252	7545 ±212	7705 ±205	7175 ±234	7350 ±180	—	—	129·5
120 and over	6500	8417	7011 ±224	7750 ±252	6972	7389	6854 ±261	7500 ±206	7724	7961	7125	8000	129·5

there is a very slight fall. The problem then arises of reducing these means to a smooth curve to represent the function sought.

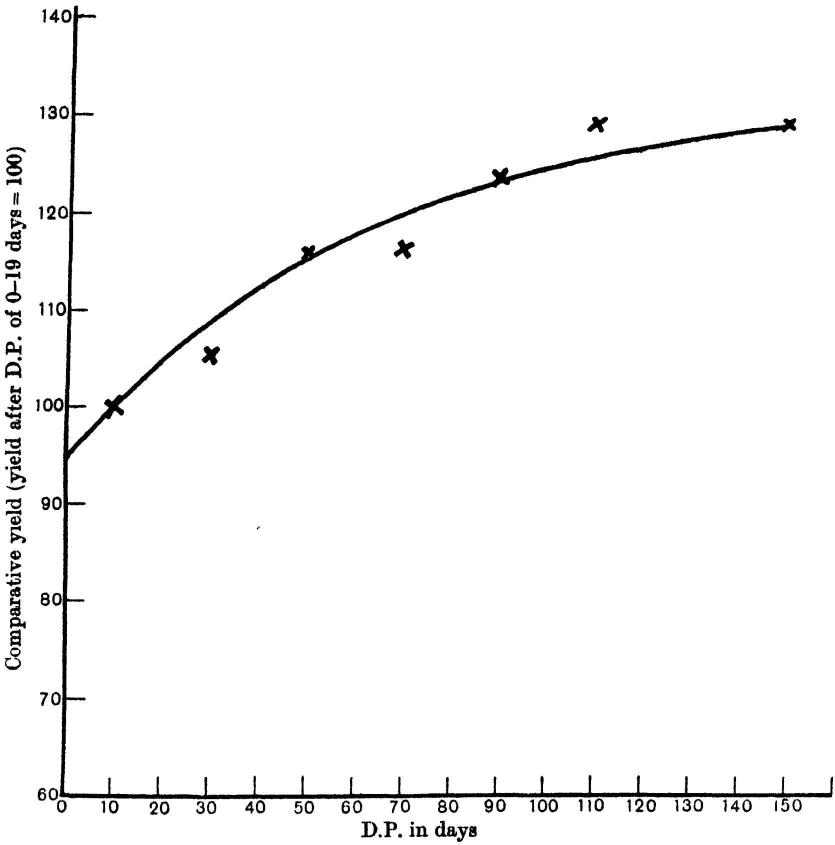


Fig. 37. Variation of yield with length of D.P.—from comparisons with D.P. – 0–19 days only.

In the last column of Table XXX are shown the comparative yields following D.P.'s falling in the other intervals, found by putting that after a D.P. of 0–19 days at 100—thus for 20–39 days we have

$$\frac{8625}{8158} \times 100 = 105{\cdot}7;$$

only the first two columns were utilised for this. A curve was then fitted to these points and is shown in Fig. 37, the equation being

$$y = 133 - 38{\cdot}3e^{-{\cdot}01573x},$$

where y = comparative yield and x = D.P. in days; it appears to give a fair fit, but the points are rather scattered.

It is required, then, to see if the other means of Table XXX, not utilised for this curve, agree with it—this is the object of Table XXXI; in the first column are the comparative yields given by the above curve; this gives a figure of 108·9 associated with D.P.'s of 20–39 days; working from this we can compute the comparative yields for longer D.P.'s from the means given by the comparisons in the 3rd and 4th columns of Table XXX—*e.g.*

$$108{\cdot}9 \times \frac{8377}{8156} = 111{\cdot}9;$$

similarly the 3rd column starts at 115·4 and from the means in columns 5 and 6 of Table XXX the figures below that were calculated.

Table XXXI. *Comparative Yields after varying lengths of D.P.*

D.P. (days)	Smoothed value given by curve in Fig. 37	From comparisons with yields following other D.P.'s, with those after: 20–39 days	40–59 days	60–79 days	80–99 days	100–119 days	Arithmetical average excluding figures in brackets
0–19	100·0	—	—	—	—	—	100·0
20–39	108·9	(108·9)	—	—	—	—	108·9
40–59	115·4	111·9	(115·4)	—	—	—	113·6
60–79	120·2	114·8	123·7	(120·2)	—	—	119·6
80–99	123·6	116·9	121·7	118·2	(123·6)	—	120·1
100–119	126·2	117·9	122·8	122·8	126·6	(126·2)	123·3
120 and over	129·4	120·4	122·3	131·5	127·4	141·7	128·8

On the whole the agreement is fairly good, but it appears that the other columns do not show quite so much rise as the first, for 11 out of the 15 figures are below the corresponding ones from the curve. Each figure (except those in brackets) in Table XXXI is really an estimate of the comparative yield concerned, and we have one estimate for D.P.'s of 20–39 days, 2 for 40–59 days, etc.; consequently the arithmetical averages of these estimates were taken, and are shown in the last column, as the final points obtained for this variation.

This procedure may not be strictly correct mathematically, but it is believed to serve the required purpose satisfactorily; no very great divergences are involved and the final figures agree fairly closely with those in the first column (the rise is somewhat "toned down") and there seems no doubt that they are more accurate. It only remains then to smooth out these figures; the fitted curve is shown in Fig. 38; its equation is

$$y = 129 - 33{\cdot}9e^{-{\cdot}01626x}.$$

The points obtained lie very close indeed to this curve throughout.

This figure also contains the corresponding curve found for 2nd

calvers; for purposes of comparison it was thought better to redraw this curve so as to cut the one obtained here at D.P. = 40 days; this has been seen to be the standard that must be taken for this factor, representing as it does the length of D.P. which has the same effect on the next lactation yield as the average effect of all D.P.'s, and therefore

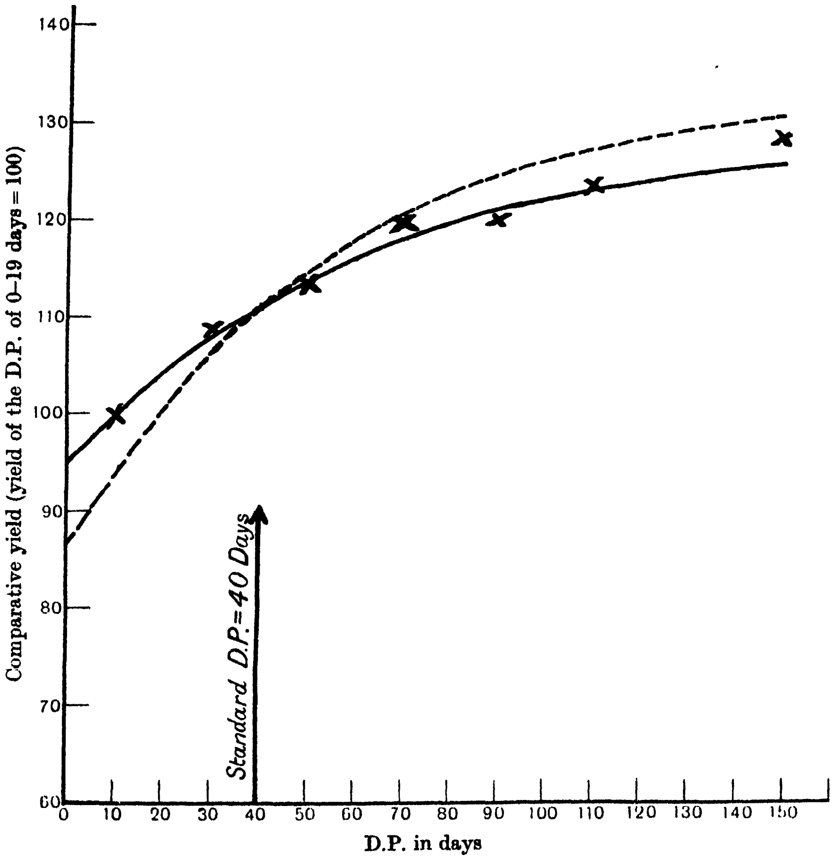


Fig. 38. Variation of yield with D.P.

Old cows (final figure) ———— × ×   2nd calvers (fig. 36) - - - - - -

the only one to give corrected yields comparable to those for the 1st lactation, where no D.P. is involved. This method of representation makes it very clear that a short D.P. before the 2nd lactation lowers the yield to a much greater extent than does a short one before one of the later lactations, and similarly a long D.P. has a more beneficial effect on 2nd calvers.

The continuous curve in Fig. 38 provides the necessary basis for calculating corrections for older cows; these are given in Table XXXII.

Table XXXII. *Corrections for Length of D.P. (other than 2nd Calvers).*

Standard = 40 days; value of curve for D.P. of 40 days = 111·2.

D.P. (days)	Comparative yield from smooth curve	Corrections for older cows %
0–9	97·5	+ 14·0
10–19	102·2	8·8
20–29	106·2	4·7
30–39	109·6	1·5
40–49	112·6	− 1·2
50–59	115·0	3·3
60–69	117·1	5·0
70–79	118·9	6·5
80–89	120·4	7·6
90–99	121·7	8·6
100–109	122·8	9·4
110–119	123·7	10·1
120 and over	126·0	11·7

It must be admitted that the great difference in this effect between 2nd calvers and others was not suspected, but it was only when this difference was realised that any semblance of continuity emerged in the results. (It should perhaps be pointed out that only a very small part of this difference can be due to increase in age, for the additional correction for 2nd calvers with D.P.'s of 0–9 days is 11 per cent. and this can hardly be attributed to 40 days increase of age.) There seems only one reasonable explanation—during the D.P. a cow gets in good condition again for the succeeding lactation, but a 2nd calver not only does this, but also, if given the chance, makes further growth too; is it bodily growth or the growth of the mammary gland that is the cause of this?

Supposing it were the latter (*i.e.* that mammary growth is limited except when the cow is dry) it would be expected that a heifer not dry at all after her 1st lactation, would give 14 per cent. less milk in the 2nd lactation than she did in the 1st—*i.e.* would not get any age increase and would suffer the same disadvantage as older cows from lack of rest; under ordinary circumstances there is a rise of 10·7 per cent. (see last Part) from the 1st to the 2nd lactation, so that the total correction for no D.P. before the 2nd lactation would be (roughly) 14 + 10·7 = 24·7 per cent.—*i.e.* in very close agreement with that found. The fallacy in this arises, however, in the fact that in this period of life the yield

in the first 10 weeks of the lactation rises by 23·3 per cent. and this has been supposed to be a better measure of the amount of mammary tissue; furthermore this index of mammary growth is 16·4 per cent. from the 2nd to the 3rd lactation, and we should therefore expect intermediate corrections for this factor for 3rd calvers; this was not found, but possibly because of insufficiency of data and the "carry-over" effect.

In this respect the variation in yield with foetal growth must not be forgotten; it was concluded that the fall in yield (slight at first, but rapid after the 20th week of pregnancy) was due to mammary growth and recommissioning—*i.e.* that the latter could occur whilst the cow was still in milk; if this is so, absence of rest between lactations would not prevent all mammary growth, in fact if the argument could be carried so far we should conclude that the gland grew 23 per cent. of its original size, normally, before the 2nd lactation, and that half of this occurred when there was no rest, the expression of the increase being prevented by whatever factors may be responsible for the effect of D.P. with older cows.

From the practical point of view, however, the chief interest lies, not between bodily and mammary growth, but between nutrition (*i.e.* storage of food reserves for the next lactation) and growth; if the former is the chief cause of the effect which the D.P. has been shown to have, it should be possible to escape the bad effects of a short D.P. by feeding heavily during the closing stages of the preceding lactation. The "carry-over" effect, to be described below, seems to suggest strongly that growth is a strong, if not the only factor as regards the D.P.; furthermore, if nutrition is the only factor it would be expected that high yielders would be affected more than low yielders by the length of the D.P.—a slight tendency towards the reverse has been found. Fortunately data is rapidly accumulating in which it is hoped that it will be possible to attack this question, with hopes of success.

At present we can only conclude that the effect is definitely greater with 2nd calvers, than with older cows, presumably because in addition to whatever factors (possibly nutrition and "recommissioning") may be concerned in all cases, the growth factor is operating much more powerfully with young cows; whether we are to understand by this bodily, or mammary growth, must be left to the future to decide.

Accumulated D.P. The attempt to evolve a system of correction to allow for the complete effect of all periods of rest an individual had, failed, because dividing the lactations up, both by the D.P. associated

Table XXXIII. *Variation of Yield with D.P., and with D.P. before the previous Lactation* (429 *2nd Calvers and* 297 *others*).

D.P. before lactation of which comparative yield is included (days)	2nd calvers (no previous D.P.)	Mean comparative yield of those with a D.P. before the previous lactation of (days)												Mean of all except 2nd calvers
		0–9	10–19	20–29	30–39	40–49	50–59	60–69	70–79	80–89	90–99	100–109	110–119	120 and over	
0–9	79·3	72·5	(1) 87·5	(1) 162·5	(1) 67·5	—	—	—	—	—	—	—	—	—	83·7
10–19	88·1	77·5	94·0	(1) 117·5	(5) 110·5	(1) 117·5	(1) 132·5	—	—	—	—	—	—	—	96·0
20–29	98·0	(3) 67·5	(3) 87·5	106·1	(2) 127·5	(1) 72·5	(2) 110·0	(1) 87·5	(1) 147·5	(1) 97·5	(2) 110·0	—	—	—	99·6
30–39	96·3	(2) 82·5	(2) 87·5	101·4	104·0	106·2	(3) 107·5	(2) 130·0	(1) 87·5	(1) 112·5	(2) 102·5	(2) 112·5	—	(1) 142·5	104·5
40–49	95·0	(3) 99·1	93·3	107·5	(1) 82·5	—	(1) 97·5	(2) 117·5	(2) 115·0	(1) 92·5	(1) 112·5	—	—	(1) 152·5	104·0
50–59	108·2	(2) 90·0	(1) 87·5	105·5	(3) 112·5	(3) 107·5	(2) 95·0	(3) 84·2	(3) 102·5	—	(2) 140·0	—	—	—	104·6
60–99	109·7	91·3	(5) 90·8	104·8	123·0	87·8	109·6	106·6	122·5	115·3	113·1	105·0	120·0	136·4	112·4
100 and over	116·2	(2) 85·0	92·5	(2) 85·0	95·4	121·2	(3) 89·2	(2) 97·5	117·5	105·0	(1) 92·5	(3) 117·5	(2) 105·0	(3) 115·8	104·5
Mean of all	98·6	81·1	91·6	105·5	109·0	104·6	105·1	104·9	117·1	109·4	111·2	110·6	109·2	136·4	105·6

with them, and also by that before the preceding lactation, reduced the observations in the final "cells" to a few individuals. Table XXXIII is, however, of some interest, as it demonstrates that *short* D.P.'s do have a "carry-over" effect.

The figures used for this table were those used for the 1st Method above—*i.e.* the comparative yield of young cows with their 1st lactation yield as 100. The column on the left gives the D.P. before the lactation itself—*i.e.* the lactation of which the comparative yield is included; next follows the comparative yield following that D.P. for 2nd calvers (already given above) and the remaining columns give the mean comparative yields of all the others, split up according to the D.P. before the previous lactation.

The numbers of observations were very low—wherever a mean included five or less lactations the actual number is given, and also in one direction those with D.P.'s of 60–99 days and all over 100 days, have been grouped together; for the 297 lactations (*i.e.* excluding the 2nd calvers) the means for all are given in both directions—*i.e.* in the last column the means of all those cows after D.P.'s of varying length are given, and at the foot their means according to varying D.P.'s before the previous lactation.

Despite the irregularity both series of means show a rise—that is to say, there is a rise in yield following not only a rise in the D.P. associated with the lactation, but also following a rise in the D.P. before the previous lactation. The means at the foot of the table actually show the "carry-over" effect we are seeking, and it will be seen that the first two are definitely down, whilst there is no more than a tendency (if that) to rise with the others. This leads to the interesting indication that D.P.'s of less than 20 days (in the case of young cows) not only lower the next lactation yield, but also affect the yield in the one after that; it would be very interesting to follow the analysis one step further and ascertain if the later lactations still are influenced, but obviously the numbers do not permit of any further division.

One point must not be forgotten here, and that is the correlation that exists between the two D.P.'s involved; this might be supposed to be responsible for the rise shown at the bottom, but the body of the table negatives such a supposition; the first two columns (*i.e.* for previous D.P.'s of 0–9 and 10–19 days) show the same thing throughout; the yield is down to 72·5 after two D.P.'s of less than 10 days, but it is still in the neighbourhood of 90 when the D.P. before the lactation itself was 60 or more days and the previous one less than 10 days—*i.e.* it

varies with the D.P. associated with it, but is depressed throughout by the previous short one.

It is unfortunate that the table is so bare in the upper right corner, for we have no indication as to the effect of a short D.P. when the one before had been long; we have, however, the information that a D.P. of 0·9 days appears to lower the yield in the next but one lactation by about 10 per cent.—apparently whatever the length of the next rest may be—and one of 10–19 days lowers it, roughly, 5 per cent. This suggests that growth is a large factor with young cows, and that if one opportunity be missed it cannot be made up at the next—for why should not nutritional losses be made good at the next chance?

This is further emphasised by the fact that there does not seem to be so much of an effect of accumulated D.P. with older cows; it was necessary to test this but only rough indications could be obtained. All cows of which the 1st lactations were known were taken as young cows, and those in which it was not known as old ones; the division was not clear cut by this procedure, but only a little over-lapping occurred; the numbers were very small but the results are suggestive.

Taking all those cows which had two consecutive D.P.'s of less than 20 days, the following mean corrected lactation yields were obtained:

	After 1st short D.P. lb.	After 2nd short D.P. lb.
53 old cows	8599	8061
24 young cows	8771	7500

Thus, there was a further drop of 6·3 per cent. following the second short D.P., with old cows, but for young ones there was a corresponding figure of 14·5 per cent.—*i.e.* over twice as great.

This problem is of great interest, but its solution is difficult; obviously these results can only be regarded as indications, but nevertheless they suggest strongly that there is a definite "carry-over" effect of a short D.P. (*i.e.* less than 20 days) and that this is much more pronounced with young cows; with these young animals there is the further indication that the harm done cannot be entirely remedied by a long rest at the next opportunity, but this could not be tested for old cows.

Section B. The Effect of the Length of the D.P. on the Lactation Curve.

We have seen that the shape of the lactation curve is affected by the other three factors and the variations in it caused by them have helped materially in explaining the variations in the total lactation yield; we have now to see how the curve is influenced by the length of the D.P.

The work was restricted to the Mongrel group and, owing to the individual tendency to the same length of D.P., it was rather difficult to get extremes with the same cow. Two comparisons, however, were possible, and have been made:

I. Between the mean curves of 42 cows after
   (A) D.P.'s of 0–19 days and
   (B) D.P.'s of 40 or more days.

II. Between the mean curves of 60 cows after
   (*a*) D.P.'s of 20–39 days and
   (*b*) D.P.'s of 60 or more days.

Table XXXIV. *Details of Lactations used to find effect of length of D.P. on the Lactation Curves.*

	1st comparison		2nd comparison	
	(A) D.P. = 0–19 days (Mean = 10·8 days)	(B) D.P. = 40 or more days (Mean = 73·2 days)	(*a*) D.P. = 20–39 days (Mean = 29·5 days)	(*b*) D.P. = 60 or more days (Mean = 88·6 days)
January calvers	5	2	3	5
February ,,	7	6	14	6
March ,,	5	8	5	7
April ,,	2	2	3	2
May ,,	4	1	3	2
June ,,	1	1	1	5
July ,,	4	4	9	3
August ,,	—	2	4	5
September ,,	2	1	7	4
October ,,	4	5	6	4
November ,,	5	3	2	8
December ,,	3	7	3	9
2nd lactation	11	2	16	7
3rd ,,	5	14	12	21
4th ,,	9	9	14	12
5th ,,	7	7	9	8
6th ,,	7	5	2	6
7th ,,	2	5	4	3
8th ,,	1	—	2	3
9th ,,	—	—	1	—
Mean S.P.	80·4 days	88·5 days	90·2 days	73·7 days
Mean uncorrected lactation yield	7205 lb.	8949 lb.	7309 lb.	7955 lb.
Mean lactation yield corrected for month of calving, Age and S.P.	7831 ,,	9406 ,,	7951 ,,	8747 ,,
Above corrected for D.P.	8849 ,,	8795 ,,	8190 ,,	8047 ,,

In this we have, as before, each cow as a "control" to herself; where one animal had two D.P.'s falling into one group the lactation taken was the one nearest (in point of age) to that taken for the other

group—if one was each side, then the younger. Table XXXIV gives the distributions of Month of Calving and Age, and the mean S.P.'s and Total Lactation Yields of these groups.

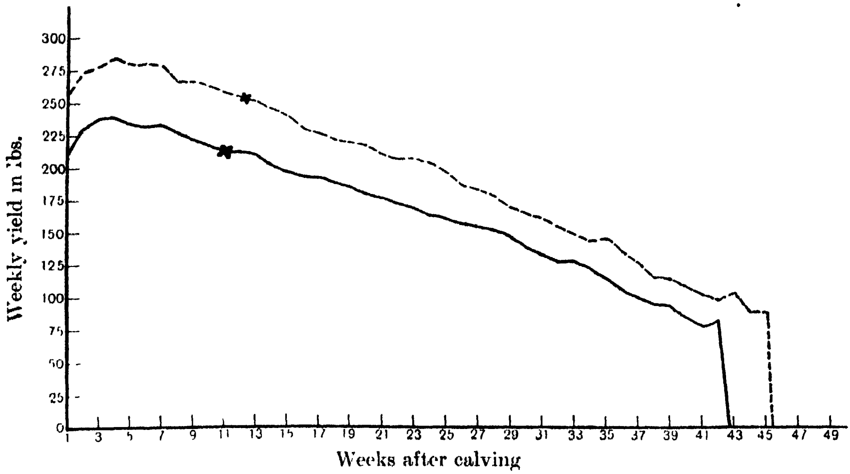


Fig. 39. Effect of length of D.P. in lactation curve.
I. 42 cows after (A) D.P. 0–19 days ———— (B) D.P.—40 or more days - - - -

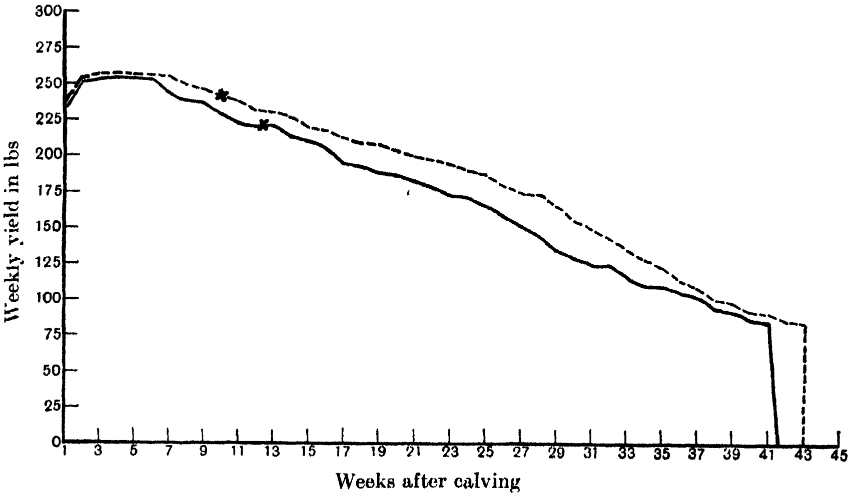


Fig. 40. Effect of length of D.P. in lactation curve.
II. 60 cows after (*a*) D.P. - 20–39 days ———— (*b*) D.P. = 60 or more days - - - - -

On the whole the Month of Calving distributions compare fairly well in each case—thus it is clear that they did not all calve in the same month for each curve, but on the other hand, they did not move forward or

backward more than a month or two. The Age distributions are very similar for lactations later than 3rd—in each case there are just as many 2nd and 3rd calvers in each curve, but it will be seen that the short D.P. groups contain more 2nd calvers and the long D.P. groups correspondingly more 3rd calvers.

There is only 8 days' difference in the mean S.P.'s in the first comparison, but 16½ days in the second; the yields corrected for all four factors agree very closely indeed in each case, showing that in their variation with the length of D.P. these cows conform well to the normal.

The mean curves given for these two comparisons are shown in Figs. 39 and 40; they have not been corrected in any way.

The point of interest is whether the increase following the long D.P. is attained by a bigger flow early in the lactation, or by the flow keeping up better—*i.e.* is "capacity" or "persistency" improved; one thing is clear—namely that the long D.P. groups have a longer lactation, for in I their S.P. is only 8·1 days, whilst their length of lactation is 18·5 days more, and in II they maintain their flow 9·5 days longer, despite being served 16·5 days earlier.

A useful figure for testing "persistency" has been found to be the ratio of the total lactation yield to the maximum (daily) yield; for (A) this figure is 210·1 and for (B) 219·9 –*i.e.* the latter is 4·7 per cent. higher; from the Month of Calving distribution we should expect (B) to give a slightly higher figure, but only by 0·5 per cent. Similarly for (*a*) the figure is 200·8, as against 216·8 for (*b*)—a rise of 8 per cent. and only 1·5 per cent. of this can be due to the calving distribution.

We have, then, that, in each case, the length of lactation and persistency of yield are greater following the longer D.P.; this is the more striking as we have seen that the short D.P. groups contain a larger number of 2nd calvers, in which the persistency figure is normally higher than for older cows (cf. Part III).

It is hoped, in the future, to treat this subject more exhaustively, by including all the cows whose D.P.'s are known; at present we can only conclude that a short D.P. does not act chiefly by lowering the maximum yield, in fact it is indicated that it is rather the persistency that suffers. This is in agreement with the results of Eckles and Palmer (1) who found that when the plane of nutrition of the cow was high, the maximum yield was not significantly increased, but the drop due to the progress of the lactation was staved off. Other workers have found contrary results—Gavin (2), for instance, finding that the maximum

(revised maximum) was lowered by 5–6 per cent. when the D.P. was less than 35 days.

Confusion appears to arise as a result of failure to discriminate between the results obtained by considering the plane of nutrition and by the actual length of the D.P.—the latter, presumably, includes the former, and also measures the opportunity for (mammary) growth. Where the plane of nutrition is the basis only the persistency is found to be affected, where the length of the D.P. is considered both are influenced, but the maximum rather less than the persistency. This is in complete agreement with the view that two factors are involved in the variation of yield with that of the length of the D.P.—growth (chiefly mammary except, possibly, for young cows) and nutrition.

Section C. Breeds—Comparison of Milking Capabilities.

So far any comparison between the milking capabilities of the various breeds and crosses represented in these data has been avoided; this question must now be faced. We have found practically no evidence of any breed peculiarities in the effects of the four factors studied, but there are some differences in their incidence—*e.g.* Red Polls suffer under the double handicap of having short S.P.'s and D.P.'s, on the average; consequently the breeds are compared both by their raw lactation yields and also by their yields corrected for all four factors.

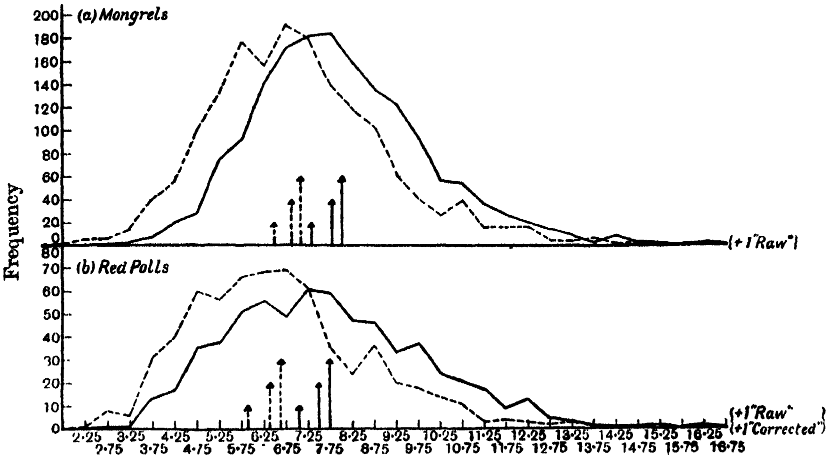
Table XXXV. *Constants for Breeds from Raw Totals.*

Breed	Mean (lb.)	Median (lb.)	Approximate* mode (lb.)	Standard deviation (lb.)	Coefficient of variation	Skewness	No. of lactations
Friesians	7899 ± 86	7521	6765	2499 ± 61	31·64 ± 0·84	+0·454 ± 0·033	383
Mongrels	7071 ± 34	6868	6462	2032 ± 24	28·74 ± 0·36	+0·300 ± 0·019	1661
Friesian Crosses	6918 ± 77	6720	6324	2022 ± 51	29·23 ± 0·85	+0·294 ± 0·041	315
Non-Pedigree Shorthorns	6700 ± 75	6614	6442	1670 ± 53	24·93 ± 0·83	+0·155 ± 0·047	228
Red Polls	6639 ± 56	6390	5892	2116 ± 40	31·87 ± 0·66	+0·353 ± 0·028	642
Lincoln Reds	6629 ± 55	6429	6029	1792 ± 39	27·03 ± 0·63	+0·335 ± 0·033	476
Park	6377 ± 159	6150	5696	1985 ± 112	31·13 ± 1·93	+0·343 ± 0·084	71
Pedigree Shorthorns	5986 ± 120	5700	5128	1819 ± 85	30·39 ± 1·55	+0·526 ± 0·060	104
Jerseys and Guernseys	5816 ± 197	5333	4367	1799 ± 139	30·94 ± 2·61	+0·805 ± 0·078	38
All cows	6940 ± 22	6713	6259	2082 ± 16	30·00 ± 0·25	+0·327 ± 0·011	3918

* Approximate mode = Mean—3 (Mean-median).

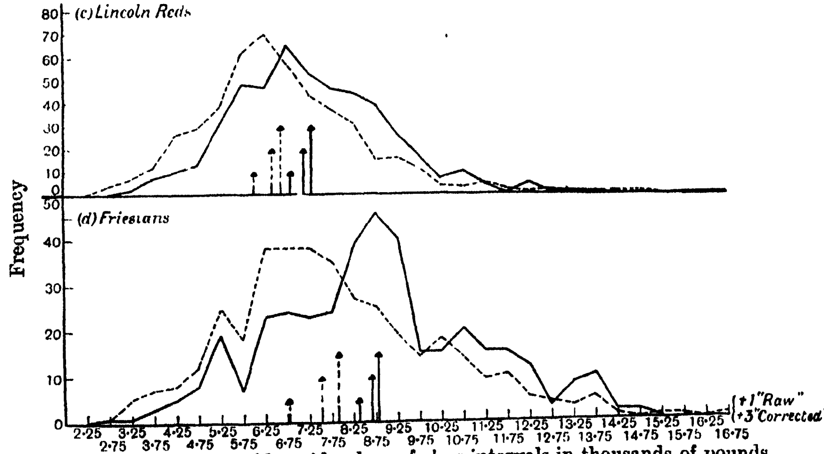
The distributions for the four major breeds represented are shown in Fig. 41 (*a*, *b*, *c* and *d*) where the continuous line shows the frequency distribution of corrected yields, and the broken one of raw yields; the means, medians and modes (approximate) are represented by small lines of decreasing length at the base; correction, it will be seen, moves the whole distribution up somewhat (cf. next Section). The scale for frequency varies from breed to breed, very roughly according to the number

of lactations included, and the scale runs up to 16,999 lb., including all the observations except three raw ones and four corrected ones.



Total lactation yield—mid-values of class intervals in thousands of pounds

Fig. 41 (*a* and *b*). Distribution of raw and corrected total lactation yields.
Raw yields - - - - - Corrected yields ———



Total lactation yield—mid-values of class intervals in thousands of pounds

Fig. 41 (*c* and *d*). Distribution of raw and corrected total lactation yields.
Raw yields - - - - - Corrected yields ———

The constants derived from the distribution of raw yields for all breeds are given in Table XXXV and those from corrected yields in Table XXXVI; in both cases the breeds are arranged in order of their means.

Table XXXVI. *Constants for Breeds from Corrected Totals.*

(Totals corrected individually for Month of Calving, S.P., Age and D.P.)

Breed	Mean (lb.)	Median (lb.)	Approximate mode (lb.)	Standard deviation (lb.)	Coefficient of variation	Skewness	No. of lactations
Friesians	8805 ± 86	8657	8361	2507 ± 61	28·47 ± 0·75	+0·177 ± 0·040	383
Mongrels	8010 ± 33	7786	7338	1982 ± 23	24·74 ± 0·31	+0·339 ± 0·018	1661
Friesian Crosses	7858 ± 72	7624	7156	1902 ± 51	24·20 ± 0·69	+0·369 ± 0·039	315
Red Polls	7727 ± 61	7499	7043	2292 ± 43	29·66 ± 0·61	+0·298 ± 0·039	642
Non-Pedigree Shorthorns	7384 ± 65	7213	6871	1465 ± 46	19·84 ± 0·65	+0·350 ± 0·047	228
Park	7377 ± 192	7106	6564	2401 ± 136	32·55 ± 2·03	+0·339 ± 0·084	71
Lincoln Reds	7300 ± 53	7141	6823	1723 ± 38	23·60 ± 0·54	+0·277 ± 0·034	476
Jerseys and Guernseys	6895 ± 174	6599	6007	1589 ± 123	23·05 ± 1·88	+0·559 ± 0·096	38
Pedigree Shorthorns	6659 ± 103	6461	6065	1564 ± 73	23·49 ± 1·16	+0·380 ± 0·067	104
All cows	7848 ± 22	7630	7194	2077 ± 16	26·47 ± 0·22	+0·315 ± 0·011	3918

Mongrels show a fairly regular, moderately asymmetrical curve; Red Polls give quite a different form—with raw totals the curve is distinctly flat-topped and this is markedly accentuated in the curve for corrected totals; this breed appears to be very diverse in its capabilities, and the data plainly showed that there was a large variation from herd to herd, some owners apparently favouring the beef type, and others working for improved milk yields; it is peculiar that Lincoln Reds (another "dual-purpose breed") do not show any tendency to this greater dispersion, though this may be due to the absence from Norfolk of any purely beef herds of Lincoln Reds. Friesians give a different type of curve again, but in this connection the small number included must not be forgotten; the curve is somewhat suggestive of a trimodal form—showing a high and a low yielding group and a much bigger medium one; the low numbers however preclude the conclusion that this throws any light on the inheritance of milking capability (*i.e.* that some single blending factor is largely responsible for this function), especially as no signs of the same thing are seen in the other breeds.

With raw totals the coefficient of variation for all cows is exactly 30, and this is reduced to 26·47 by correction (see next Section, however, for a discussion of this); Red Polls, as is clear from their distribution, give a high figure, as do Friesians and Park Cattle (71 only); Lincoln Reds show less variability as do Non-Pedigree Shorthorns. The skewness is positive in every case and, with all cows, is little changed by correction.

The order of merit is only slightly altered by correction, Red Polls and Park move up one place and Lincoln Reds and Non-Pedigree Shorthorns descend. Fig. 42 shows the comparison; at the left the breeds are entered according to their mean raw total yields, and at the right according to their mean corrected total yields. For purposes of adjusting the Month of Calving corrections, all totals were corrected,

en bloc, for Service and later for Age, and the means arrived at by that procedure are shown in the centre of the figure; in each case all means were multiplied by a constant factor to bring them down to the original level, so that it can be seen whether or not the system of correction

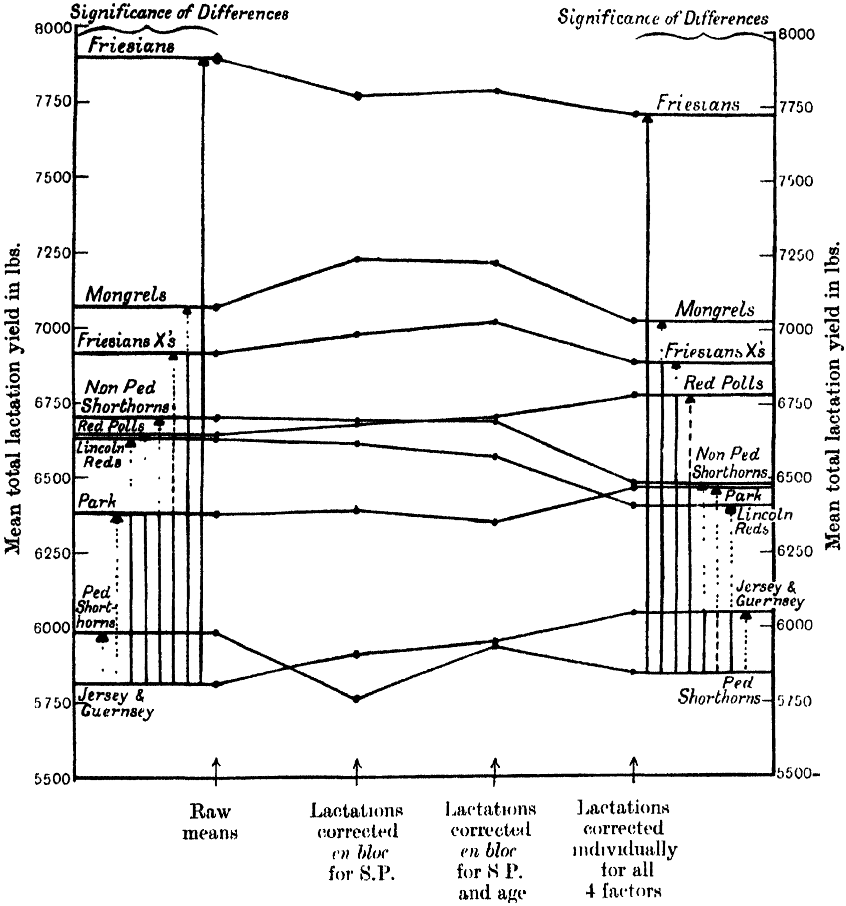


Fig. 42. Comparison of breeds

Difference = Over 4 times its probable error ————
Between 3 and 4 times its probable error - - - - -
Less than 3 times its probable error · · · · · ·

raised or lowered any breed relatively to the others. The limits of significance are also shown at the sides for raw and corrected (individually) means; differences equal to or greater than 4 times their probable errors are marked with a continuous vertical line, between 3 and 4 times, with a broken one, and less than 3 times with a dotted line.

For instance, taking Non-Pedigree Shorthorns (raw yields) the vertical lines show that their differences with Friesians and Mongrels are both significant, as also with Pedigree Shorthorns and Jerseys and Guernseys; their differences from Red Polls, Lincoln Reds and Park are, however, less than 3 times the probable errors.

Friesians head the list with both uncorrected and corrected means, and it is seen that the several differences between this breed and all the others are significant (*i.e.* greater than 4 times their probable errors). Mongrels take the second place, and, again in both cases, are significantly above all those below them, except Friesian Crosses. Friesian Crosses are significantly above Pedigree Shorthorns and Jerseys and Guernseys, and, when corrected, also Lincoln Reds.

Red Polls and Lincoln Reds give approximately the same raw means, but, when corrected, the former moves up noticeably, and the latter down, so that in the last column Red Polls are significantly higher; it will be seen that the movement of Red Polls upwards is principally due to S.P. and D.P. corrections, whilst the downward movement of Lincoln Reds is caused by correction for the long D.P.'s usually associated with them.

Non-Pedigree Shorthorns also descend markedly because of their long D.P.'s. Park, Pedigree Shorthorns and Jerseys and Guernseys are not sufficiently represented in these data to allow much reliance to be placed on their positions; Park and Jerseys and Guernseys go up and Pedigree Shorthorns down, the latter finishing at the bottom of the list.

It is believed that this figure gives a fairly true comparison between the milking capabilities of the breeds recorded in Norfolk; the books of every member of the M.R.S., with one exception, were obtained, and although a good many lactations had to be omitted for lack of details, there is no reason to suppose that this acted unequally on the various breeds. It must be left to the reader to decide how far these records are fair samples of the breeds as a whole, but it seems probable that they are, within a little, representative of them, as they exist in this country[1].

Section D. The Standardisation of Yields.

The Efficiency of the Corrections.

When the final corrections necessary to standardise yields for S.P., Age and D.P., had been ascertained, each of the 3918 lactations included

[1] For the shape of the lactation curves of the different major breeds included, see Part I, Section B.

was corrected separately for these three factors; in doing this 5 per cent. was added on for Age in every case where that variable was unknown, and 5 per cent. subtracted where the D.P. was unknown; this procedure was based on the fact that Age was unknown only with older cows—*i.e.* no 1st calvers and probably very few 2nd calvers—and on the probability that hardly any unknown D.P.'s were short, otherwise the end of the preceding lactation would have been seen. In only a small percentage of the lactations did these corrections apply, and it is probable that on the average they were justified, though, as intended, they erred, if anything, on the side of under-correction.

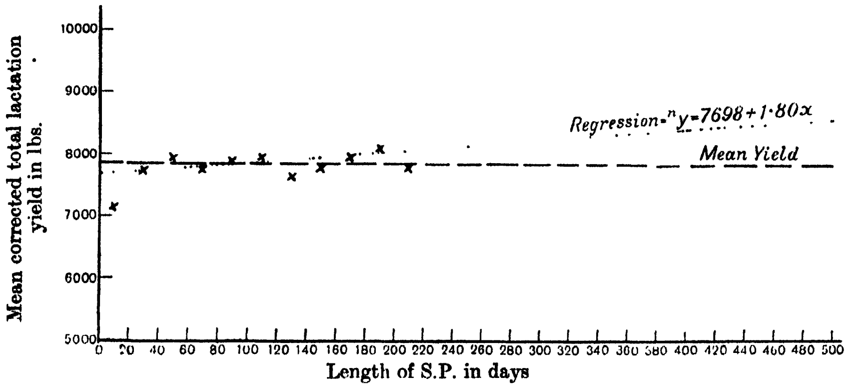


Fig. 43. Association between corrected yield and length of S.P. (all cows).

From these corrected yields the final figures for each Month of Calving were obtained (cf. Part I), and then the corrections for that variable, as finally amended, were applied to the yields. The resulting figures—*i.e.* yields corrected individually for all four factors—have been used to compare breeds in the last Section.

Some interest lies in the variation of these corrected yields with the various factors, as affording a good test of the validity of the figures used; the variation with Month of Calving is not given, as obviously, by the method of procedure, it must vanish—because the last step has been to correct that variation to a straight line—but those with S.P., Age and D.P. are given below.

Fig. 43 shows the relation found between the corrected total lactation yield and the length of the S.P.

For S.P.'s of 20 to 220 days the points conform very closely indeed to the general mean—*i.e.* the variation shown in Part II has been successfully eliminated. For the whole table the correlation coefficient

was found to be $+ 0{\cdot}047 \pm 0{\cdot}011$, a very small value but just significant; but this is clearly due to two groups:

(1) Those with S.P. = 0–19 days give a low mean; this question has already been discussed (Part II) and the low figure has been deemed to be due to the fact that high yielding cows do not come in season so early in the lactation—*i.e.* that this mean is based on cows below the average. The difference of this mean from that of all cows is 719 ± 243[1] lb. or 2·96 times its probable error; since we have taken 4 times the probable error as constituting significance, it will be quite consistent to ignore this difference.

(2) Those with S.P. = 220 or more days give a high mean; here the difference from the general mean is 663 ± 129[1] lb., or 5·14 times its probable error, and hence significant; this might arise as a result of only those cows that maintain their flow better than normal being kept after S.P.'s of that length; that is, if they come down to a low level when unserved for so long, they are fattened, and so do not appear in these data, having no S.P.

In view of the entire absence of any sign of relationship

$$(r = + 0{\cdot}006 \pm 0{\cdot}011)$$

for S.P.'s between 20 and 220 days (a range including 96·2 per cent. of these lactations) it seems justifiable to conclude that this variation has been satisfactorily eliminated; the line $y = 7848$ lb. clearly fits the points better than the regression (dotted) line, and to reduce the two points mentioned to the same level the corrections would have to be based on a curve showing definite breaks at the beginning and end of the range—irregularities for which there appears no conceivable justification—whereas the reasons given might easily be held to explain these two, rather small, deviations.

The importance of this figure lies in the fact that the S.P. corrections were obtained early in the work, before the other factors could be allowed for, and that relations do exist between these other factors and S.P.; the figure shows that such relations have not led to inaccuracies in the S.P. corrections.

Fig. 44 gives the relationship between the corrected total lactation yield and the age of the cow.

A very rough curve has been drawn (dotted) through these points; it will be seen to be horizontal for lactations 1–5; the point given by

[1] Probable error from the formula (3),

$$\epsilon_{01}^2 = \sigma^2 \frac{n_2}{n_1(n_1+n_2)}.$$

1st calvers is slightly above, but the difference from the general mean is only 99 ± 41 lb. (see footnote to p. 236) or 2·4 times its probable error, and so is insignificant.

The actual deviation of these 1st calvers suggests that the correction applied is about 1·2 per cent. too much; in fitting a curve for the effect of age, where 1st lactation = 100, the actual curve cuts the line for heifers at 98·5—that is, that fitting practically exactly accounts for this deviation. This result is eminently satisfactory, as it shows that a standard of 40 days for the D.P. corrections for *older cows* was correct,

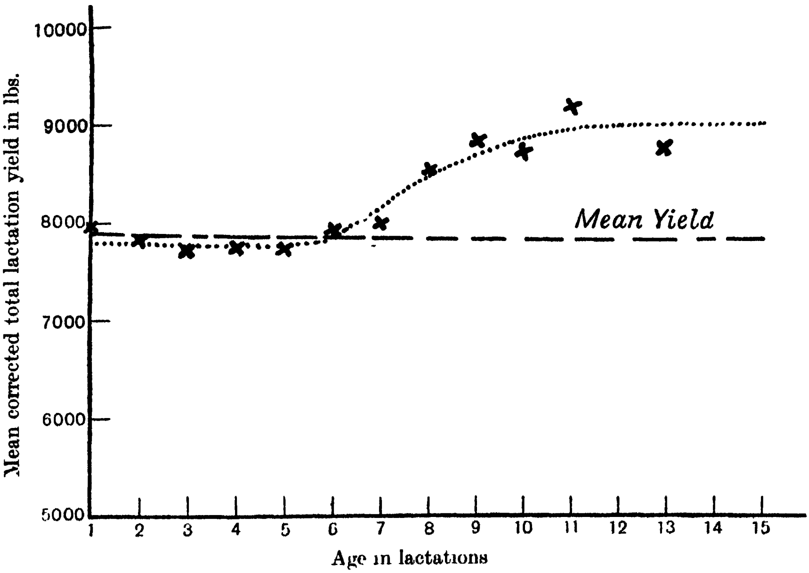


Fig. 44. Association between corrected yield and age (all cows with age known).

in that it gave a figure comparable to the corrected yields of 1st calvers; this was seen to be the case for 2nd calvers, but had to be assumed for older cows.

Selection for milk production is not operating very highly, apparently during the first five lactations, but it is seen to be a potent factor from the 5th to the 10th lactation; this, presumably, is the stage of life when the inferior milkers are culled. As regards the earlier ages, it is possible that there is a greater incidence of pathological conditions with higher producers, and this may mask any selection that is being carried out.

Fig. 45 shows the relation between the corrected total lactation yield and the length of the D.P. preceding the lactation.

Here the relationship is very plain; the correlation coefficient is

$-0{\cdot}327 \pm 0{\cdot}012$—a significant negative value—and the figure shows that the regression line fits the means very well, with the possible exception of the last point (27 observations).

This, of course, is in agreement with the results found for high and low (total) yielders (Part I), the former showing markedly lower mean length of D.P., but it is surprising to find here that there is such a definite linear correlation—*i.e.* that over the whole distribution the better the milker the nearer to the next calving, on the average, is the yield maintained. The D.P. is only long for the worst cows (with few exceptions) and it will be remembered that the standardising corrections had to be determined by comparison of the yields given by the same cows in different lactations, and not by comparison of different cows.

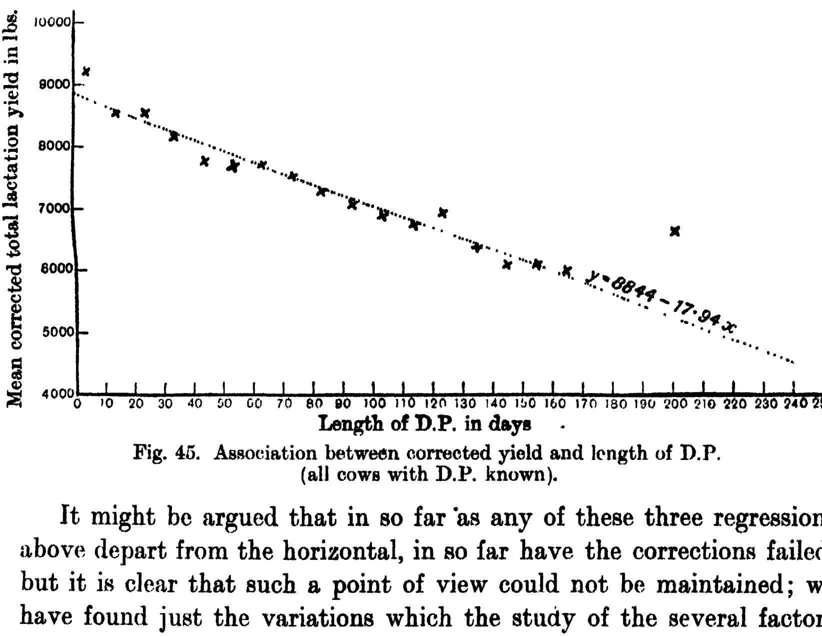


Fig. 45. Association between corrected yield and length of D.P. (all cows with D.P. known).

It might be argued that in so far as any of these three regressions above depart from the horizontal, in so far have the corrections failed, but it is clear that such a point of view could not be maintained; we have found just the variations which the study of the several factors has led us to expect, and this is claimed as very strong evidence that, in the method used, the interrelations between the factors, which must necessarily somewhat complicate such an investigation, have not given rise to inaccurate corrections. The corrections appear then to be right, on the average, and their efficiency when applied to the yields of individual cows is dealt with below.

Fig. 46 shows the distribution of raw and corrected yields of all cows, the constants for which have been given in Tables XXXV and XXXVI.

The distribution of corrected totals is of some interest, because it is at least an approximation to the variation in the "genetic makeup" as regards milk yield, of Norfolk cows, when all are standardised in respect of the four factors studied; for this reason the "normal curve" corresponding to this distribution is given also (dotted). The corrected totals do not conform very closely to the normal distribution, their curve being steep at the lower end of the range, and the mean is raised by a rather greater than normal proportion of very high producing cows (skewness $= +0{\cdot}315 \pm 0{\cdot}011$).

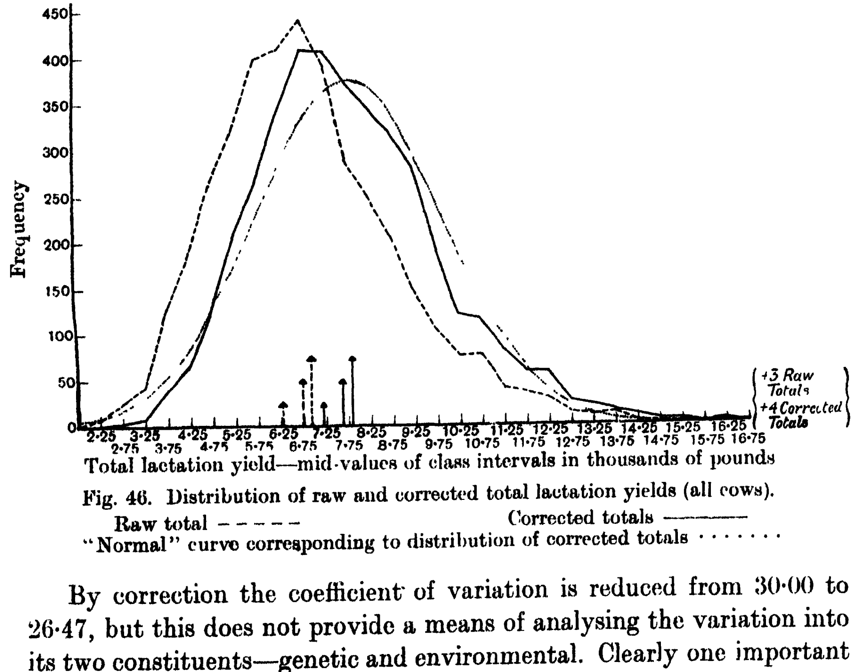


Fig. 46. Distribution of raw and corrected total lactation yields (all cows).
Raw total - - - - - Corrected totals ———
"Normal" curve corresponding to distribution of corrected totals · · · · · · ·

By correction the coefficient of variation is reduced from 30·00 to 26·47, but this does not provide a means of analysing the variation into its two constituents—genetic and environmental. Clearly one important factor operating (D.P.) tends to narrow the difference between the good and bad milker, and correction, therefore, in this respect definitely widens the range. Furthermore the environmental variation is not all eliminated by correction; in the next section it will be seen that the corrected yield may vary by 8 per cent. from its true value. But the chief environmental variation which yet remains, is that due to variations in feeding and management from herd to herd; until it is possible to assess a value to different systems, and standardise records made under different conditions, considerable error must be introduced in comparing cows of different herds. Much knowledge remains to be

gained before this can be, even roughly, accomplished, and it must be emphasised that this method of standardisation is intended primarily to allow of the comparison of the performances of cows of the same herd; standardisation is rendered possible in respect of every factor except "feeding and management"—though the elimination of this factor cannot be carried out, it is recognised as a potent one, and must, by no means, be forgotten.

The Reliability of the Estimate.

In an Appendix are given the percentage corrections which have been found necessary to allow for the variations caused by these four factors; they are self explanatory. It will be seen that for any circumstance that raises the yield in a lactation (*e.g.* October calving, long S.P. and D.P.) there is a negative correction, and for any that lowers the yield (*e.g.* June calving, short S.P. and D.P., and any lactation but the 6th) there is a positive correction. When the percentages have been applied to a cow's lactation yield, the figure calculated is an estimate of what that particular cow will give when mature (*i.e.* in her 6th lactation) under standard conditions—these being defined as:

(1) Calving in a "mean" month—approximately March and September.

(2) Being served 85 days after calving—*i.e.* so as to calve again in exactly a year's time.

(3) Having been dry for 40 days before the lactation.

These will be recognised as perfectly normal conditions; the total effect of the corrections is to raise the yield, on the average, by about 13 per cent., principally because all the age corrections are positive. It seemed better, however, not to adjust the age corrections so as to give, on the average distribution of that factor, a corrected yield approximating to the raw one (*i.e.* for a number of cows), for the final estimate would then have little meaning; the estimate given by these figures on the other hand is a definite forecast of a particular lactation yield.

The Month of Calving effect is small compared to the others, the corrections varying from − 4·7 per cent. to + 7·0 per cent., and it must be remembered that with feeding and management well above the average, much of this would probably be eliminated.

In contrast with this we have the large corrections for the length of the S.P., varying from + 28·2 per cent. to − 33·3 per cent. for 1st calvers, and from + 33·9 per cent. to − 30·8 per cent. for others. Practical men

have, of course, always realised that some account must be taken of the length of the interval between calvings, and the practice has arisen of stating, in describing a record, the number of days in milk; it is difficult to defend this practice, for the statement that a cow gave 800 gallons of milk in 300 days is, at best, unsatisfactory, and, at worst, positively misleading; if this cow is due again in another week or fortnight her performance is very much better than if she has only just been served. If this has any real effect on the propagation of the species, it can only lead to the production of cows which give a lot of milk in the early part of the lactation, and it has been shown that selection based on this is wrong, in that it will tend to lower the persistency of the secretory function, which accounts for something like half of the superiority of first-class animals. Furthermore this indefinite sort of statement does not permit of any correction, and the time is fast coming (or has already come) when the best farmers will require to know how allowance can accurately be made for the increase or decrease in yield caused by the interval between calvings. The S.P. is an easy concept, and the statement that this cow gave 800 gallons with a S.P. of 40 days has a definite meaning, and these corrections will show how to estimate what her yield would have been, if the interval between calvings had been of the normal length of one year. Is it too much to hope that corrections such as these may shortly be absorbed into practice, instead of the totally unsound and indefinite idea of the length of the lactation?

Age is another potent factor and 30·6 per cent. must be added on to a heifer's yield in order to estimate her yield at the prime; for administrative purposes, of course, the age of the cow, and not the number of lactations she has had, must be the basis; corrections for that, however, can readily be obtained by reading 3 years old for 1st lactation. 4 years for the 2nd and so on.

The length of the D.P. also is a large cause of variation, the corrections ranging from + 25·1 per cent. to − 14·8 per cent. for 2nd calvers and from + 14·0 per cent. to − 11·7 per cent. for others; these represent the variation caused under present normal conditions, but the reservation must be made that it is possible that this may be halved by high feeding, though whether this applies equally to young and old cows, must be left for the future to decide.

It must be remembered that the percentages given for S.P. and D.P. are based on continuous variations, and are only strictly accurate for the mid-points of the intervals; thus the correction for S.P. = 80—99

days is $-1\cdot1$ per cent., and this corresponds to an actual S.P. of 89·5 days—clearly for S.P.'s of 80 to 84 days a positive correction should be applied; this can easily be obtained by interpolation with as much accuracy as is required.

Usually little error is introduced by adding the percentages together and applying them as one; it will be realised that they are of the form $1+a$, $1+b$, $1+c$, $1+d$, where a, b, c, d are the corrections given (*i.e.* for June calving $a = +7/100$); the total correction is, then,

$$(1+a)(1+b)(1+c)(1+d) \text{ or } 1+\Sigma a+\Sigma ab+\Sigma abc+abcd.$$

By simply adding the percentages the figure applied is $1+\Sigma a$—*i.e.* all higher terms are neglected; this is only justifiable when the corrections are small. For instance, to correct a 1st calver with a S.P. of 389 days the corrections are $+30\cdot6$ per cent. for age and $-30\cdot5$ per cent. for S.P., or $+0\cdot1$ per cent. by addition; by multiplication however the total correction is

$$\left(1+\frac{30\cdot6}{100}\right)\left(1-\frac{30\cdot5}{100}\right)=90\cdot8,$$

or a correction of $-9\cdot2$ per cent. This is an extreme case, the error being clearly 1 per cent. with two corrections of 10 per cent., 4 per cent. with two of 20 per cent. and 9 per cent. with two of 30 per cent.

In correcting these lactations, account was taken of this error in every case where there was one correction to be applied, of as large as 10 per cent., and another as large as 20 per cent. (*i.e.* for two corrections of $+10$ per cent. and $+20$ per cent. the true figure should be $+32$ per cent. and not $+30$ per cent.). The method then recommended is to work backwards in the history of the lactation; that is to correct first for the length of the S.P. and get an estimate for the cow's worth after calving, then for Month of Calving and get the estimate at the time of calving, then for D.P. and get her level at that age, and finally for age. With practice, correction can be done very quickly—in the ordinary run of lactations the writer has found it easy to average 100 an hour when the necessary details are ready to hand.

We come then to the final question, namely, what is the estimate worth, when it has been obtained, as a measure of the cow's milking capabilities? For this purpose the 190 cows with 654 lactations, mentioned in the last section, were used; the mean of all the corrected totals of each cow was found, and her several corrected yields expressed

as ± a percentage of this mean; for instance two cows gave the following:

Cow A.

1st lactation, raw yield	= 7129 lb., corrected yield	= 9367 lb., deviation	= + 0·1
2nd	= 6960	= 9438	= + 0·9
3rd ,,	= 8073	= 9383	= + 0·2
4th ,,	= 8453	= 9245	= − 1·2
Mean	7654	9358	

Cow B.

1st lactation, raw yield	= 6466 lb., corrected yield	= 8307 lb., deviation	= + 1·6 %
2nd ,, ,,	= 6831 ,, ,,	= 7705 ,,	= − 5·8 ,,
3rd ,, ,,	= 8885 ,, ,,	= 9065 ,,	= + 10·8 ,,
4th ,, ,,	= 7376 ,, ,,	= 7635 ,,	= − 6·6 ,,
Mean	7389	8178	

The first is given as an example of how all cows should behave, and the second as one of the sort of result usually obtained.

Frequency distributions were then drawn up of these percentage deviations, and these gave the results shown in Table XXXVII.

Table XXXVII. *Percentage Deviation of Corrected Totals from the Individual Mean.*

Lactation	No. included	Mean deviation %	Probable error of the percentage deviations (*i.e.* 0·67449 × σ) %	Semi-interquartile range (*i.e.* range within which half of the deviations lie) %
1st lactation	190	− 0·00	8·94 ± 0·31	8·08 ± 0·51
2nd ,,	190	+ 1·55	7·76 ± 0·27	7·47 ± 0·44
3rd ,,	190	− 0·97	7·61 ± 0·26	6·57 ± 0·43
4th ,,	84	− 0·83	8·23 ± 0·43	7·50 ± 0·71
Lactations 2, 3 and 4	464	+ 0·09	7·83 ± 0·17	7·55 ± 0·28
All lactations	654	+ 0·05	8·17 ± 0·15	7·72 ± 0·25

For the first 3 lactations there are 190 observations and 84 for the 4th, as the 106 cows with lactations 1–3 only, drop out here; the mean deviation is not in any case significant, which means that the age corrections have, on the average, satisfactorily disposed of that variation. Next follows the probable error of the distribution, or 0·67449 × the standard deviation; with 1st calvers this is nearly 9 per cent., and it sinks to 7·76 per cent. and 7·61 per cent. for the next two, rising to 8·23 per cent. for the 4th; the latter is raised by one cow that gave a deviation of + 48 per cent. in the 4th lactation, for which no explanation can be offered. The probable error for lactations 2, 3 and 4 taken together is 7·83 per cent., and for all 654 lactations 8·17 per cent.

The last column shows, however, that the estimate is slightly more trustworthy than this would lead us to expect; here we have the range

that includes half of the deviations, and this is only just over 8 per cent. for 1st calvers and about 7½ per cent. for the others, giving a mean of 7·72 per cent. for all. The standard deviation (and hence the probable error) is raised by a small proportion of cows that, for some reason unobtainable from the records, suddenly changed their plane of production altogether, and so it may be that the semi-interquartile range is a better measure of the distribution, which is shown in Fig. 47 together with the corresponding "normal" curve.

It will be seen that the frequencies in the two intervals about zero are noticeably greater than those shown by the curve; for the interval 0 to + 5·0 per cent. the difference is 21 ± 6·36, and for 0 to − 5·0 per cent. it is 9 ± 6·36 per cent.; the frequencies for deviations of from ± 5·0 per cent. to ± 25·0 per cent. are all less than given by the curve and after that they become greater. From the actual distribution we find that

25	per cent.	of the deviations	are	less than	3·39	per cent.
37	,,	,,	,,	,,	5·00	,,
50	,,	,,	,,	,,	7·72	,,
75	,,	,,	,,	,,	13·55	,,
90	,,	,,	,,	,,	19·77	,,

Table XXXVIII gives the corresponding figures to those in Table XXXVII for Breeds, and high and low yielders separately; the latter were divided according to their mean corrected yield.

Table XXXVIII. *Percentage Deviation of Corrected Totals from the Individual Mean.*

Class	No. included	Mean deviation %	Probable error of the percentage deviations (*i.e.* 0·67449 × σ) %	Semi-interquartile range (*i.e.* range within which half of the deviations lie) %
Mongrels	276	+0·04	8·30 ± 0·24	7·69 ± 0·39
Red Polls	100	+0·20	8·98 ± 0·43	9·13 ± 0·71
Lincoln Reds	129	+0·10	6·77 ± 0·28	7·21 ± 0·47
Friesians	63	+0·28	9·44 ± 0·57	7·44 ± 0·94
High yielders	320	+0·12	7·80 ± 0·21	7·07 ± 0·34
Low yielders	334	+0·03	8·52 ± 0·22	8·49 ± 0·37
All cows	654	+0·05	8·17 ± 0·15	7·72 ± 0·25

Mongrels and Friesians show a greater probable error but a smaller semi-interquartile range than do all cows, and the difference may very well be due to chance; with Red Polls and Lincoln Reds the latter figure is a little greater than the former, showing that the distributions are flatter. Red Polls show a greater variation and Lincoln Reds less

than the others, the difference in the probable errors being 2·21 ± 0·51 per cent., which is significant; the writer believes that this is to be attributed to the fact that practically all the successive short D.P.'s for young cows were for Red Polls; in correction no account was taken of the "carry over" effect demonstrated in Section A of this Part, and it is probable that this provides the explanation of the greater apparent variability of Red Polls.

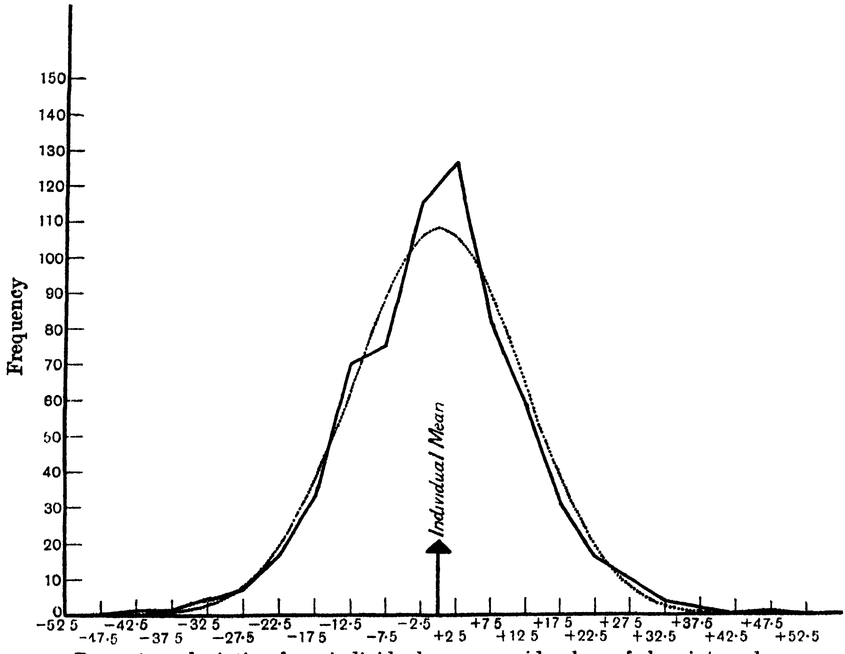


Fig. 47. Frequency distribution of percentage deviation of corrected totals from the individual means.

Frequency found ———— Normal curve ······

Low yielders show rather more variation than do high yielders; the difference in the probable errors is 0·72 ± 0·30 per cent.—*i.e.* 2·4 × its own probable error—and that in the semi-interquartile ranges is 1·42 ± 0·50 per cent., or 2·8 × its own probable error; while neither of these is significant, they do give an indication that, after correction, there is rather more percentage variation about the individual mean with low yielders than with high yielders.

We have been led, then, to the conclusion that the estimate obtained by the application of these corrections is subject to a probable error of

9 per cent. in the case of 1st calvers, and 8 per cent. in the case of older cows, and that this applies approximately equally to all breeds and grades of producers. The statistician, however, has to take all records which comply with his requirements with regard to details, etc., and it is probable that the owner of the cow could lay his finger on the cause of any great deviation from the previous or subsequent plane of production, and it is a few cases of this kind that are responsible for raising the probable errors to a high degree. With the exercise of the necessary common sense, it is believed that the estimate reached would provide a trustworthy means of discriminating between the milking capabilities of different cows, and it is clear such a discrimination would be of immense value to a farmer in weeding out his worst cows, in selection for breeding, in correctly apprising a cow's performance when buying, and in studying pedigrees.

The agricultural research worker is continually faced with the problem of deciding whether any result is really reliable or not, and in work on milk secretion this problem is usually incapable of solution; by the application of these corrections a figure may be obtained to represent a cow's lactation yield to which is attached a *known* probable error (8 per cent.) and hence a simple calculation will show the amount of reliance that may be placed on a result, to the point of knowing the odds against its being due to chance. With more knowledge it may be found possible to reduce this probable error; as it is, it is within the realm of practical politics to plan an experiment which may be expected to give a definitely significant result, and such, after all, is at least the next best thing to that rarity in Agricultural Research—the Critical Experiment.

Summary.

This paper describes a statistical analysis of the records collected by the Norfolk Milk Recording Society (3918 lactations), comparing the results with those obtained from the records of the Penrith M.R.S. (already published).

As in the case of Penrith, autumn calvers were found to average more milk in a lactation than spring calvers, but the best months of calving were two months later—*i.e.* October to February instead of August to December; this is because in the case of Norfolk, yields are maintained well throughout the winter, whereas they fall off very rapidly in the Penrith district from February to April, and if this bad period comes early in the lactation a low yield results. The yield falls

off, in both districts, very rapidly during summer (after the flush of grass in spring) and particularly during the two periods June-July and September-October; the average rates at which the yield declines during different calendar months, appears to provide the explanation of the variation in yield according to the month of calving. Seasonal variations appear to be nutritional, rather than meteorological, in nature, and it seems probable that with more knowledge of feeding and management they should be largely eliminated; the greatest scope for improvement lies in summer, when it is suggested arrangements should be made for a supply of catch-crops for feeding green, and this supplementing of the grass should begin much earlier in the year—*i.e.* beginning of June in normal seasons—than is generally believed.

On the average these Norfolk cows had an interval of almost exactly 1 year between calvings; heifers were found to maintain their flow for a fortnight longer than older cows served at the same stage of the lactation, and this, together with the flat-shaped curve given by heifers, led to the result that the variation of yield in the lactation, with the interval between calving and service, though similar in form, differs slightly in amount, between these two groups. Following service the yield drops very slightly and remains below the level for unserved cows for 20 weeks, at which point the cow begins definitely to dry off; whilst the results for all cows agreed exactly with those from the Penrith data, there was found to be a certain amount of variation from breed to breed and from high to low yielders in this. On the evidence it is difficult to believe that this effect is due to nutritional causes; it is possible that it is the outcome of the preparation of the mammary gland for the next lactation, which apparently begins very early in pregnancy; there is, however, a definite intensifying of the effect (or some other effect is superimposed) round about the 20th week of pregnancy.

The usual variation of yield with age has been found, but this had to be measured by building up a continuous curve from individual cows' yields, as farmers only keep their better cows after the 5th or 6th lactation; the yield increases by 30 per cent. from the 1st to the 6th lactation and then decreases at exactly the same rate, on the average, though there is considerable variation in the case of old cows, senility probably being rather pathological than physiological. A study of average lactation curves showed that the increase in yield in the time before maturity is obtained entirely in the early part of the lactation.

The length of time a cow was dry, before the commencement of the lactation, was found to have a large effect on her yield; with 2nd calvers

this effect is much greater and it is suggested that this is because, in addition to whatever factors may be operating with old cows, young ones make growth if allowed a fair rest; whether we are to understand this as bodily or mammary growth it is difficult to decide, but probably the latter is the more important. In the same way it cannot be said whether older cows reap a benefit from a long rest by getting in good condition ready for the strain of the next lactation, or because it allows the mammary gland a better chance of preparation; very tentatively half of the total effect might be due to each of these two causes, but this very important practical question will soon be capable of solution. The length of the dry period appears to affect the yield, approximately equally, throughout the next lactation.

High and low producing cows vary in the same proportion with these factors, except, perhaps, that the latter increase to a rather greater extent, in their flow, with age. The difference between the yields of these two groups was found to be apportionable as follows: $\frac{1}{2}$ to the physiological capacity, as measured by the maximum yield, and $\frac{1}{2}$ to persistency of the flow; the latter may be subdivided into $\frac{3}{10}$ as being due to the yield keeping at a relatively higher level throughout, and $\frac{2}{10}$ to its being maintained longer. It is pointed out that not only is the maximum yield unsound as a basis for selection, but if used as such can only lead to a decline in the persistency factor.

Although there were differences in the average productions of the several breeds represented in these data, they appeared to vary in the same way, and very much to the same extent with these four factors; Lincoln Reds and Red Polls, though giving very much the same level of production, always tend to depart slightly from the normal, and invariably in opposite directions; this is particularly the case in the effect of foetal growth on the yield. If there is any variation in these effects it does not appear to be between "dual-purpose" and purely dairy breeds, but between large and small breeds; the differences, however, were not statistically significant.

Corrections were calculated throughout, to allow for these four factors and to give a standardised figure to the cow, to serve as a basis for comparison; the same figures (given in the Appendix) were found to be applicable to the various breeds and to high and low yielders.

It is believed that it is fundamentally wrong to investigate the action of one of these factors alone, for they are, to a certain extent, interrelated; the method adopted was chosen as giving the best chance

of escaping the errors introduced by the associations between them, and evidence is produced that such errors have been avoided.

The final estimate reached, by the application of these corrections, is subject to a probable error of 9 per cent. in the case of 1st calvers, and 8 per cent. in the case of older cows; the distribution of deviations about the cow's mean, showed, however, that these figures are raised more than normally by a very small proportion of animals which gave very wide fluctuations. Presumably there were, in some of these cases, reasons assignable to the wide deviations, but as no note was made in the record, they had to be included in this invest[illegible] in the hands of the farmer, therefore, it is probable that the [illegible] would be more trustworthy than appears from the probable error, and it is believed that the corrections might be of considerable practical use, if employed with a reasonable admixture of common sense; in particular, it is urged that the corrections for the intervals between calvings, based on the time of service, are just as easy to understand, and much more dependable, than the length of the lactation idea now in vogue. There also seems a possibility of the use of these figures in experimental work, as the results obtained would be subject to a known error, and consequently their meaning readily interpreted, and significance appreciated; the individuality of the cow is the great stumbling-block in research on milk secretion, and this can only be overcome by using the same animal as a "control" to herself; with long term experiments this necessitates the accurate estimation of the fluctuations caused by these four factors.

It is impossible, in a short note, adequately to acknowledge my indebtedness. Thanks are due to all those ladies and gentlemen who forwarded to me their records, to provide a basis for this study, and, in particular, to Mr Bugg, the Secretary of the Norfolk M.R.S., to Mr Twinch the Live Stock Officer of the district, and to the Live Stock Branch of the Ministry of Agriculture and Fisheries, for their assistance in the collection of the data. Mr G. Udny Yule, F.R.S., has always readily given me the great benefit of his knowledge of the Science of Statistics, effectively banishing any mathematical difficulties that arose, and the kindly help and sympathetic interest of Dr F. H. A. Marshall, F.R.S., have been much appreciated. To Mr J. Hammond, M.A., my gratitude is especially due; not only did he first show me the importance of the lactation curve, as the only means of getting down to the causes of these variations, but also, throughout the work, has always been

Appendix—Standardising Corrections.

I. Month of Calving
Standard—Mean of all months

Month of calving	Correction %
January	−0·9
February	−2·8
March	−0·2
April	−2·2
May	+3·4
June	+7·0
July	+5·0
August	+3·0
September	+0·5
October	−4·7
November	−2·6
December	−3·8

II. Length of Service Period
Standard—S.P. = 85 days

	Correction	
S.P. in days	1st calvers %	Others %
0–19	+28·2	+33·9
20–39	+18·4	+21·3
40–59	+10·6	+11·9
60–79	+ 4·2	+ 4·6
80–99	− 1·1	− 1·1
100–119	− 5·5	− 5·9
120–139	− 9·2	− 9·7
140–159	−12·4	−12·9
160–179	−15·2	−15·5
180–199	−17·6	−17·8
200–219	−19·7	−19·7
220–239	−21·5	−21·4
240–259	−23·1	−22·8
260–279	−24·5	−24·1
280–299	−25·8	−25·1
300–319	−27·0	−26·1
320–339	−28·0	−26·9
340–359	−28·9	−27·6
360–379	−29·8	−28·3
380–399	−30·5	−28·8
400–419	−31·2	−29·3
420–439	−31·8	−29·8
440–459	−32·4	−30·2
460–479	−32·9	−30·5
480–499	−33·3	−30·8

III. Age of the Cow
Standard—Maturity = 6th lactation

Age	Correction %
1st lactation	+30·6
2nd ,,	+18·0
3rd ,,	+ 9·3
4th ,,	+ 3·7
5th ,,	+ 0·7
6th ,,	—
7th ,,	+ 1·4
8th ,,	+ 4·8
9th ,,	+10·4
10th ,,	+18·5
11th ,,	+29·4
12th ,,	+43·7

IV. Length of the Dry Period
Standard—D.P. = 40 days

	Correction	
D.P. in days	2nd calvers %	Others %
0–9	+25·1	+14·0
10–19	+15·2	+ 8·8
20–29	+ 8·0	+ 4·7
30–39	+ 2·8	+ 1·5
40–49	− 1·3	− 1·2
50–59	− 4·4	− 3·3
60–69	− 6·4	− 5·0
70–79	− 8·8	− 6·5
80–89	−10·4	− 7·6
90–99	−11·7	− 8·6
100–109	−12·7	− 9·4
110–119	−13·5	−10·1
120 and over	−14·8	−11·7

ready to place at my disposal his vast store of practical and theoretical knowledge of this very wide subject; full advantage has been taken of this opportunity, and a large part of any merit that may be found in these pages must be attributed to him. My thanks must also be recorded to my wife for her assistance in the more humdrum part of the work.

REFERENCES.

(1) ECKLES and PALMER (1916). "The Influence of the Plane of Nutrition of the Cow, upon the Composition and Properties of Milk and Butterfat. Influence of Over-feeding." *Mo. Agric. Exp. Sta. Res. Bull.* **24**.

(2) GAVIN (1912). "The Interpretation of Milk Records." *Journ. Roy. Agric. Soc. of England*, **73**.

(3) YULE (1912). *An Introduction to the Theory of Statistics*, London, p. 346.

(*Received December 10th*, 1927.)

AN INDEX OF SOIL TEXTURE.

By F. HARDY, M.A., Dip.Agr. (Cantab.).

(*Imperial College of Tropical Agriculture, Trinidad, British West Indies.*)

The need of a single-value constant for assessing soil texture for purposes of field mapping, has long been felt. It is difficult to derive such a constant from data obtained by mechanical soil analysis. The following considerations suggest that a single-value constant, derived from a measurement of moisture content of a soil at the point of stickiness, together with a determination of the sand fraction, may satisfy the requirements of reconnaissance surveys of undeveloped lands, such as occur in the tropics.

Theoretical Considerations.

Considerable evidence may be adduced in support of the view that, at the point of stickiness[1], the water content of a moist kneaded *clayey soil* occurs mostly in association with its colloidal component, which it saturates (Hardy (1)). Its magnitude may therefore be taken as an approximate measure of the degree of colloidality or "clayiness." The constant may easily and accurately be determined for clayey soils, without the employment of any apparatus other than a balance and a drying oven.

When applied to *sandy soils*, however, the method fails to yield correlative results, because the moisture content of a coherent wet mass of sand is unassociated with colloidal matter, but occurs instead entirely as films and wedges that bind together the component particles. The magnitude of the interstitial moisture content of coherent wet sand has been assessed by mathematical calculation and by experiment (Keen (3), Wilsdon (4), Wright (5)). The value yielded by these investigations approximates to 20 *per cent.* of the mass of the dry material. Theoretically, this figure is a constant for all sandy soils, irrespective of the size of their component particles, provided packing is maximum. Hence attempts to measure the moisture content at the point of stickiness for colloid-free sand, should yield values approaching 20 per cent. In

[1] The term "point of stickiness" is preferable to the term "point of maximum plasticity" as used somewhat loosely by some writers. The two states are not coincident. The colloid component of a soil is believed to be saturated with water at the point of stickiness, but not quite saturated at the point of maximum plasticity.

practice, however, the point of stickiness is difficult to determine in the extreme cases of sandy soils.

Natural soils may be regarded as mixtures of sand and colloidal matter in various proportions. The colloidal matter probably occurs therein mainly as coatings covering the sand grains. At the point of stickiness, the moisture content of the composite material may not all be associated with the colloid component. A part of it may occur as films and wedges around and between the colloid-coated sand particles. If it be assumed that 20 per cent. of the mass of the sand content gives a measure of the quantity of water occurring as films and wedges, then the remainder of the water must be associated with the colloidal component, and its amount should give a fairly reliable measure of the degree of colloidality of the soil, no matter what the proportionate amounts of colloid and of sand may be. In other words, this correction for the quantity of sand present in a soil sample should yield a truer estimate of clayiness than a determination of the moisture content at the point of stickiness alone. The corrected figure may be termed "the index of texture." Thus,

$$\text{Index of Texture} = \text{Moisture Content at Point of Stickiness} - \frac{\%\ \text{Sand}}{5}$$

or

$$\text{I.T.} = P - \frac{\%\ \text{Sand}}{5}.$$

Indices of texture of soils belonging to any one soil-type may be plotted on plans in colours by reference to an arbitrary colour scale, and descriptive names may be assigned to the soils according to their indices. The following table (Table I) suggests suitable colours and names for use in mapping. The lower limit of index of texture clearly is zero (*i.e.* for sands), (20 – 100/5); the upper limit is a high positive number, which has been found by trial to be less than 60 for the most clayey soils.

Table I.

Index of texture		Colour for mapping	Designation
Mean	Range		
60 and above		Purple	Very heavy clay
57·5	(60 to 55)	Blue	Heavy clay
50	(55 to 45)	Blue-green	Clay
42·5	(45 to 40)	Green	Heavy silt
35	(40 to 30)	Yellow	Fine silt
25	(30 to 20)	Orange	Heavy loam
15	(20 to 10)	Pink	Light loam
5	(10 to 0)	Red	Sand

APPLICATION TO A SOIL SURVEY.

The writer has applied the method to a soil survey of the sugar-cane lands of the island of Trinidad, B.W.I. The area so far surveyed is approximately 25,000 acres (40 square miles), comprising four large sugar estates, situated on a flat alluvial plain. Copies of field plans were obtained from the estate managers, and soil samples were taken by a spade-and-trowel method at spots marked on the plans. One sample (first foot) was taken in about every 10 acres of land. The locations of the sample-spots were decided largely by field observations of the condition of the crop, and its resistance or susceptibility to a local pest known as the froghopper. In addition, the reputation of the various fields, and their past agricultural treatment were considered in deciding locations.

The soils were air-dried in the laboratory, and sifted through a 1-mm. sieve. Determinations were made of the moisture contents at the point of stickiness on duplicate kneaded samples, each of about 50 gm. mass, moulded into the form of a flat cake.

Duplicate determinations of *sand contents* were made by a conventional beaker method (sedimentation from 7·5 cm. level in 75 sec., which separates coarse and fine sand particles, whose diameters lie between 1 and 0·04 mm.).

Few of the soil samples contained particles larger than coarse sand, so that it was not usually necessary to consider gravel fractions.

In certain instances, hygroscopic coefficients (H) were also determined (in triplicate) for purposes of checking. Occasionally also, humus contents were determined by a wet combustion method, or estimated from determinations of total nitrogen contents.

Table II presents a series of results obtained with every fiftieth soil sample taken. These results were therefore not specially selected.

Reaction values were determined, in addition, on every sample, by the quinhydrone electrode method, both for aqueous soil suspensions ("normal" reaction), and for suspensions in molar potassium chloride solution ("exchange" reaction). They were checked by the use of Comber's thiocyanate reagent. The pH values were plotted on separate field plans. In plotting indices of texture, splotches of crayon colour, corresponding to the index values, were placed on the plans at points marking the locations where the samples had been taken. As the plotting proceeded, the distribution of textural types became clearly indicated. Since the number of samples taken was very large (2000), the final spot plans could be employed to construct soil maps showing the ap-

proximate limits of the main textural types. Similar procedure yielded separate soil-reaction maps.

Table II. *Representative Results.*

Soil No.		M.P.S.	Sand %	Hygr. coeff. (H)	Index of texture (I.T.)	$\frac{\text{I.T.}}{H}$	Texture type
C	50	28·1	53·3	3·6	17·5	4·8	Light loam
C	100	47·8	22·4	9·0	43·3	4·8	Heavy silt
C	150	35·3	37·2	4·7	27·9	5·9	Heavy loam
C	200	42·4	19·0	7·3	38·6	5·2	Fine silt
C	250	45·9	9·2	—	44·1	—	Heavy silt
CA	50	44·7	13·0	9·6	42·1	4·4	”
CA	100	46·5	15·5	10·3	43·4	4·2	”
CA	150	53·8	12·0	11·0	51·4	4·6	Clay
CA	200	47·7	13·2	—	45·1	—	”
WOA	50	51·5	16·0	12·7	48·3	3·8	”
WOA	100	25·0	60·5	4·0	12·9	3·2	Light loam
WOA	150	30·8	52·0	3·6	20·4	5·6	Heavy loam
WOA	200	28·2	50·0	3·8	18·2	4·7	Light loam
WOA	250	42·1	49·0	7·6	32·3	4·3	Fine silt
WOA	300	26·0	67·5	2·7	12·5	4·7	Light loam
WOA	350	28·0	44·0	4·0	19·2	4·8	”
WOA	400	24·0	60·5	—	11·9	—	”
O	50	42·9	53·2	5·6	32·3	5·7	Fine silt
O	100	28·9	33·5	3·9	22·2	5·6	Heavy loam
W	50	45·7	13·7	11·3	43·0	3·8	Heavy silt
W	100	49·2	7·4	12·2	47·7	3·9	Clay
W	150	46·1	19·7	8·8	42·2	4·8	Heavy silt
W	200	40·9	24·6	8·0	36·0	4·5	Fine silt
W	250	26·9	46·8	3·3	17·3	5·0	Light loam
M	50	49·6	14·3	11·6	46·8	4·0	Clay
M	100	41·8	29·0	10·2	36·0	3·5	Fine silt
M	150	40·1	21·1	8·9	35·9	4·0	”

Note. The ratio I.T./H measures the "vesicular coefficient" (Wilsdon (4), Hardy (1, 2), Wright (5)). Its mean value for the soils contained in the table is 4·6. The soils are alluvial alumino-siliceous and acid.

ADVANTAGES OF THE PROCEDURE.

1. The procedure yields results quickly. The laboratory methods are extremely simple, and may be applied under proper supervision by assistants possessing no previous training.

(In the survey described, 25,000 acres of land were mapped within a year by a team consisting of three field officers, three native field assistants, one laboratory superintendent, and three native laboratory assistants.)

2. The procedure enables the surveyor to explore a large area in considerable detail, and to detect local variations in soil type which might be missed when the conventional composite-core method of sampling is employed. This advantage is best realised in surveys of flat alluvial land.

3. The finished maps have considerable practical value to field managers.

4. The texture maps, used in conjunction with the reaction maps, aid in the preparation of composite soil samples. For this purpose, portions of soil are taken from individual samples representing the main soil types, and are mixed together. The mixed samples may be employed in lime-requirement investigations, and in special soil studies that may be found necessary in advisory work.

5. The texture maps indicate the regions where it might be advantageous to take representative samples for special studies of any particular soil type, or of any particular set of soil conditions.

DISADVANTAGES.

1. The procedure yields no indication of variations in soil tilth in the field.

2. The maps delineate only the *main* soil types.

3. The procedure allows of no differentiation between soils containing various proportions of organic matter.

(Nevertheless, by grouping soils according to their appearance in the field, and then determining organic matter in the composite samples, this disadvantage largely disappears.)

SUMMARY.

1. A procedure is described for evaluating an "index of texture" (I.T.), based on determinations of moisture contents at the point of stickiness (P), and of sand contents (S) of soil samples.

$$\left(\text{I.T.} \doteq P - \frac{S}{5}.\right)$$

2. The procedure is simple, and allows of a rapid laboratory examination of a great number of spot samples, so that detailed texture maps can readily be constructed.

3. Employed in conjunction with soil-reaction maps, the texture maps form a useful basis for detailed investigations of soil genesis and soil fertility.

REFERENCES.

(1) HARDY, F. (1923). *Journ. Agric. Sci.* **13**, 243.
(2) —— (1923). *Ibid.* **13**, 340.
(3) KEEN, B. A. (1924). *Ibid.* **14**, 170.
(4) WILSDON, B. H. (1924). *Ibid.* **14**, 473.
(5) WRIGHT, C. H. (1926). *Ibid.* **16**, 18.

(*Received December* 19*th*, 1927.)

AN INVESTIGATION OF THE METHOD OF PAGE AND WILLIAMS FOR THE DETERMINATION OF THE SATURATION CAPACITY OF SOILS.

By P. E. TURNER, B.Sc., A.I.C.

(*The Imperial College of Tropical Agriculture, Trinidad, British West Indies.*)

I. Introduction.

The majority of the physico-chemical properties of a soil are believed to be due mainly to the colloidal material present. Their magnitude appears to depend on the reactivity of this soil fraction, and is a function of the area of the colloidal surface in contact with the soil solution, and the nature of the complex negative ions which constitute this surface. The chemical composition and constitution of these ions, and the area they comprise, vary from soil to soil, but remain practically unchanged in individual soils over a long period of years. Any measurable properties which depend on them serve to characterise the soil and assist in its classification.

The properties of adsorption and base exchange possessed by the colloidal complex may be used for this purpose. The affinities of its negative ions are satisfied by the adsorption of equivalent amounts of ions of the opposite sign. The ions adsorbed may, by appropriate methods, be replaced by other positive ions. The exchange is stoichiometric, and the quantity of displaced or displacing ions is capable of measurement. The value obtained, which is known as the saturation capacity of the soil, is in a sense a measure of its degree of colloidality.

II. Methods of Determining the Saturation Capacity of Soils.

The various methods proposed for the determination of the saturation capacity fall into three classes.

In one, the soil is treated with a soluble hydroxide, *e.g.* the hydroxide of an alkali or alkaline earth metal, and the amount of base reacting with the soil is determined indirectly from that remaining in solution. The method of Hissink(4) is illustrative of this class. The exchangeable hydrogen ions of the soil are estimated by neutralisation with barium hydroxide, and to the value obtained is added that of the other exchangeable cations present.

Such methods suffer from numerous defects. The quantity of soil used is known to influence the results, and adsorption proceeds to some high but indefinite pH value. Hydrolysis occurs of the salts formed by the addition of the base to the relatively much weaker soil acids, and it is difficult to obtain a precise end point. If the concentration of hydroxide is increased to minimise the extent of hydrolysis, the less stable aluminosilicate ions at the surface of the colloidal particles tend to decompose, introducing additional errors.

In the methods of the second class, the soil is leached with a solution of a neutral salt, *e.g.* the chloride of barium (1), potassium or ammonium (6). The adsorbed ions originally present are replaced by ions of one kind, which are in turn displaced by extraction with dilute acid or sodium chloride solution, and their amount determined. These methods are tedious and expensive. Four litres of extract at least must be obtained, before the reaction is approximately complete, and the filtrate differs inappreciably from the leaching solution. Washing the soil free from the salt used is a slow process, and fungus growths appear before it is in a fit condition for the determination of its content of exchangeable base.

The method of Page and Williams (7) for the estimation of the state of saturation of the soil, when in equilibrium with calcium carbonate, is typical of the third class. The moistened soil is intimately mixed with an excess of calcium carbonate, the mixture is ultimately leached with normal sodium chloride, and the amount of calcium passing into solution is ascertained according to the procedure of Hissink (5).

The following formula is given by Page and Williams to illustrate the reaction which occurs when a soil is treated with sodium chloride solution.

$$\left[\text{Soil}\right]\begin{matrix} a\text{H}^{\cdot} \\ b\,(\text{Ca}^{\cdot\cdot}+\text{Mg}^{\cdot\cdot}+\text{K}^{\cdot}) \end{matrix} + c\text{Na}^{\cdot} + c\text{Cl}'$$

$$\left[\text{Soil}\right]\begin{matrix} (a-x)\,\text{H}^{\cdot} \\ (b-y)\,(\text{Ca}^{\cdot}+\text{Mg}^{\cdot}+\text{K}^{\cdot}) \\ (x+y)\,\text{Na}^{\cdot} \end{matrix} + x\text{H}^{\cdot}$$

$$+\,y\,(\text{Ca}^{\cdot}+\text{Mg}^{\cdot}+\text{K}^{\cdot}) + [c-(x+y)]\,\text{Na}^{\cdot} + c\text{Cl}'.$$

The reaction is reversible, but the equilibrium point is continuously displaced from left to right by leaching with fresh salt solution. The displacement is slow, as the adsorbed hydrogen ions are removed from the soil with difficulty, unless calcium carbonate is present. This reacts with the replaced hydrogen ions to form carbonic acid, which is slightly ionised only, and readily decomposes into water and carbon dioxide.

The reduction of the hydrogen ion concentration of the solution in contact with the soil, which depends on the free escape of the carbon dioxide formed, hastens the completion of the reaction. As Page and Williams state, "the whole of the adsorbed hydrogen ions are in time directly replaced by sodium ions, and there appear in solution, in addition to the calcium ions directly replaced from the soil by sodium ions, a further quantity of calcium ions equivalent to the hydrogen ions originally adsorbed by the soil."

The method possesses the advantage of extreme simplicity, it is fundamentally more accurate than those of the first class and is more rapid than those of the second. It suffers from the following defects, however, and needs further examination before it can safely be used for the determination of saturation capacity.

(1) The leaching solution contains calcium ions derived by solution from the calcium carbonate present, and the reaction may, therefore, not proceed to completion. The investigations of Tjurin(8) on the content of exchangeable magnesium and calcium of soils containing alkaline earth carbonates, indicate that complete extraction may be possible in mineral, but not humus, soils.

(2) Little information exists as to the volume of leaching solution which should be used before the reaction may be considered complete. Tjurin's work indicates two litres to be insufficient.

(3) It is doubtful whether the correction usually applied for the solubility of calcium carbonate in the normal sodium chloride solution is justifiable. According to Hissink(5), if calcium carbonate is present, the amount of adsorbed calcium in the soil is equal to the difference in the quantities found in the first two litres of filtrate. This procedure is based on the supposition that the whole of the exchangeable calcium passes into solution in the first litre, and that approximately equal amounts are dissolved from the carbonate by each litre. If appreciable exchangeable calcium is present in the second litre, the results obtained by this method are smaller than the true values. Further, if Tjurin is correct, more calcium passes into solution from the carbonate in the first than in subsequent litres, thereby increasing the error.

(4) In order to measure accurately the saturation capacity, the soil content of exchangeable potassium, sodium and magnesium ions should be determined. In normal soils, however, these ions are present in minute quantities compared with the amounts of calcium and hydrogen ions adsorbed. As will be seen later, the error incurred by neglecting them is small compared with the inherent deficiencies of the method.

III. Experimental.

The various samples examined are representative of some of the soil types of the Naparima District and the Central Alluvial Plain, the two most important cane growing areas of Trinidad. The soils of these regions appear to differ greatly in many respects, but they all contain little or no humus. The samples obtained were dried at air temperature, and representative portions of 25 grm. of each were thoroughly moistened, and intimately mixed with an excess of pure precipitated calcium carbonate. 100 c.c. of hot normal sodium chloride were added with thorough stirring. The mixtures were allowed to stand at least 7 days, and were frequently shaken to assist the escape of the carbon dioxide formed. Finally, the supernatant liquid was decanted into a funnel, to which the soil was later quantitatively transferred. Whatman filter papers No. 40 were used. The soil was leached to 2 litres with normal sodium chloride solution, and the calcium contents of the first and second litres determined. The whole process was repeated on certain of the soils as a check on the accuracy of the method. Very close agreement between duplicates was obtained.

The solubility of calcium carbonate in the normal sodium chloride solution, under the conditions of the experiment, was determined independently. The first and second litres were found to contain 0·038 and 0·036 grm. of calcium oxide, respectively. These values, which include the calcium present as impurity in the leaching solution, appeared to be independent of the time taken to complete the two stages of the leaching process. The amount of CaO present in a litre of the solution of sodium chloride when saturated with calcium carbonate is 0·038 grm. Apparently the solution remains in contact with the soil mixture during the leaching process long enough for equilibrium with the carbonate to be attained.

These data do not confirm the statement of Tjurin, that the difference in the amounts of calcium passing into solution from the carbonate in the 2 litres of extract is sufficiently large to cause an appreciable error.

The necessary corrections for the solubility of the carbonate have been applied to the data appearing in Table I. These data give the amounts of calcium which pass into solution only through exchange reactions with the adsorbed ions of the soil. The saturation capacity is therefore the sum of the amounts given as present in the 2 litres.

Table I. *Calcium passing into solution through exchange reactions with normal sodium chloride solution. Soils of the Naparima District.*

Soil type and Sample No.	Sample depth (ft.)	Exchangeable calcium. Gm. CaO per 100 gm. of air-dry soil: Litre I	Litre II	Litre I + litre II	Ratio $\frac{\text{Litre II} \times 100}{\text{Litre I + litre II}}$
(1) Old alluvial:					
M 38	0–1	0·483	0·070	0·553	12·7
M 39	1–2	0·412	0·049	0·461	10·6
M 67	0–1	0·459	0·089	0·548	16·2
M 71	0–1	0·483	0·070	0·553	12·7
M 96	0–1	0·487	0·071	0·558	12·7
M 101	0–1	0·606	0·094	0·700	13·4
M 123	0–1	0·777	0·092	0·869	10·6
M 151	0–½	0·495	0·099	0·594	16·7
M 152	½–1	0·410	0·085	0·495	17·2
M 153	1–2	0·378	0·057	0·435	13·1
M 163	0–½	0·520	0·097	0·617	15·7
M 164	½–1	0·536	0·089	0·625	14·2
M 165	1–2	0·599	0·134	0·733	18·3
(2) New alluvial:					
M 40	0–1	0·870	0·126	0·996	12·6
M 41	1–2	0·924	0·094	1·018	9·2
M 190	0–1	0·809	0·121	0·930	13·0
M 191	1–2	0·704	0·071	0·775	9·2
(3) Brown:					
M 50	0–1	0·711	0·117	0·828	14·1
M 51	1–2	0·720	0·076	0·796	9·5
M 188	0–1	0·746	0·097	0·843	11·5
M 189	1–2	0·649	0·073	0·722	10·1
MH 15	0–1	0·603	0·134	0·737	18·2
MH 16	1–2	0·570	0·124	0·694	17·9
(4) Red:					
M 44	0–1	0·638	0·076	0·714	10·6
M 45	1–2	0·580	0·072	0·652	11·0
M 46	0–1	0·583	0·110	0·693	15·9
M 47	1–2	0·507	0·088	0·595	14·8
M 48	0–1	0·550	0·114	0·664	17·2
M 49	1–2	0·542	0·099	0·641	15·5
M 179	0–1	0·597	0·102	0·699	14·6
M 180	1–2	0·555	0·107	0·662	16·2
MPD 9	0–1	0·690	0·110	0·800	13·8
MPD 10	1–2	0·490	0·107	0·597	17·9
Mean value		0·596	0·094	0·690	13·9

IV. Discussion and Conclusions.

Leaching to 1 litre is insufficient to secure complete reaction between the soil mixture and the normal sodium chloride solution. Appreciable quantities of calcium oxide, varying from 0·026 to 0·097 grm. per 100 grm. of air-dry soil, and from 9·2 to 21·8 per cent. of that present in the total volume of filtrate, are removed by the second litre.

These data correspond very closely with those obtained by Gedroiz (2)

and Hendrick and Newlands (3) in their investigations on the course of replacement of the exchangeable calcium of the soil by consecutive treatments with salt solutions. Gedroiz treated 100 grm. of tshernozium soil with successive portions of 500 c.c. of normal sodium chloride solution. The procedure of Hendrick and Newlands was similar, but 92 grm. of acid Craibstone soil (of podsolic type) and 460 c.c. of solution were used. Neither soil contained carbonates. The data in Table III are taken from the account published by the latter.

Table II. *Calcium passing into solution through exchange reactions with normal sodium chloride solution. Soils of the Central Alluvial Plain.*

Sample No.		Sample depth (ft.)	Exchangeable calcium. Gm. CaO per 100 gm. of air-dry soil			
			itre I	Litre II	Litre I + litre II	Ratio $\frac{\text{Litre II} \times 100}{\text{Litre I} + \text{litre II}}$
WOA	341	0–1	·188	0·032	0·220	14·5
A	10	0–1	·221	0 026	0·247	10·5
W	71	0–1	·226	0·033	0·259	12·7
O	122	0–1	·282	0·047	0·329	14·3
CPD	1	0–1	·309	0·045	0·354	12·7
WOA	295	0–1	·297	0·068	0·365	18·6
CA	16	0–1	·340	0·050	0·390	12·8
WOA	272	0–1	·377	0·072	0·449	16·0
WOA	332	0–1	·402	0·099	0·501	19·8
WOA	320	0–1	·429	0·096	0·525	18·3
WOA	339	0–1	·443	0·096	0·539	17·8
CPD	3	0–1	·485	0·077	0·562	13·7
CA	15	0–1	·497	0·075	0·572	13·1
WOPD	5	0–1	·420	0·117	0·537	21·8
W	85	0–1	·465	0·112	0·577	19·4
WOPD	3	0–1	·573	0·074	0·647	11·4
W	48	0–1	·610	0·088	0·698	12·6
W	106	0–1	·582	0·134	0·716	18·7
W	62	0–1	·652	0·087	0·739	11·8
W	58	0–1	·639	0·122	0·761	16·0
CA	2	0–1	·702	0·158	0·860	18·4
CA	1	0–1	·768	0·197	0·965	20·4
Mean value			·450	0·087	0·537	15·7

Table III. *Calcium removed by successive extractions with normal NH_4Cl solution* (Hendrick and Newlands).

No. of extract	Gm. CaO per 100 gm. of air-dry soil	
	Tshernozium	Craibstone soil
1	0·6100	0·1264
2	0·1605	0·0200
3	0·0937	0·0096
4	0·0560	0·0064
5–10	0·1664	0·0199
Total	1·0866	0·1823
1 and 2	0·7705	0·1464
3 and 4	0·1497	0·0160

The third and fourth filtrates from the tshernozium soil, which are together equivalent to the second litre, contain 0·1497 grm. of calcium oxide, or 16·3 per cent. of the total amount removed by the first four extractions. The corresponding value for the Craibstone soil is 0·0160 grm., or 9·8 per cent. There are present in the first four extracts, 84·7 per cent. of the total calcium displaced from the former soil, and 89·1 per cent. of that displaced from the latter, by the ten consecutive treatments.

As far as the data go, the course of replacement of the calcium from these soils differs but little from that of the heaviest and lightest soils of the Central Alluvial Plain of Trinidad (CA 1 and WOA 341, respectively). Continued extraction of the Trinidad soils, especially those which are more colloidal in character, would probably therefore result in the solution of further comparatively large and significant amounts of calcium.

It appears that the presence of calcium carbonate does not hasten sufficiently the progress of the reaction to enable the saturation capacity to be measured accurately by leaching to 2 litres, according to the procedure of Page and Williams. Either leaching should be continued until 3 litres or more of filtrate are obtained, or preferably, a smaller quantity of soil should be used. In the leaching method of Joffe and McLean(6), 10 grm. of soil are employed. This amount is also recommended by Tjurin for the determination of the exchangeable calcium present in soils containing calcium carbonate.

The correspondence which exists between the absolute and relative amounts of calcium removed by third and fourth extractions, according to the procedure of Gedroiz, and Hendrick and Newlands, and those obtained in the second litre of filtrate by the method under investigation, suggests that the difficulty experienced in removing the final amounts of adsorbed ions, rather than the presence of calcium ions in the leaching solution, is responsible for the tardiness with which the reaction proceeds to completion.

The incompleteness of the reaction renders the method of Hissink inaccurate for the calculation of saturation capacity. The quantity of calcium passing into solution in the second litre, through exchange reactions alone, may be as large as 21·8 per cent. of that present in the 2 litres of filtrate. Assuming this volume of solution to be sufficient for the complete extraction of the exchangeable bases, an error of 43·6 per cent. may be incurred by the subtraction of the calcium content of the second litre from that of the first. As this assumption is incorrect, the error may attain even larger proportions.

It has been recognised of recent years that the nature of the colloidal material may vary greatly in different soils, and that such variation is in part responsible for the great dissimilarity in behaviour frequently exhibited by soils that show, by other methods, approximately equal colloid content. The lack of consistency in the character of the colloidal complex is to some extent reflected in the value of the ratio of the calcium content of the second litre to the total amount extracted. For example, this ratio is practically constant for the top soils (12·6 and 13·0 per cent.) and subsoils (9·2 per cent.) of the New Alluvial soil type. The reactivity of the colloidal fraction apparently varies with depth, but changes but little from one site to another at constant distances below the surface. The field behaviour of this soil is remarkably uniform throughout the type. On the other hand, the variation in the ratios for the Old Alluvial, red and brown soil types indicates that the nature of the colloidal material is not always constant for soils belonging to one type, and may vary irregularly with depth, and with length of cultural treatment.

The data for the soils of the Central Alluvial Plain also afford evidence of the dissimilarities which may occur in the character of the adsorbing complex of the soils of a limited area. The samples from this region are arranged in order of increasing colloidality, as determined by the total calcium extracted. The calcium contents of the first litre, with few exceptions, appear in the same order. Those of the second litre increase with fair regularity at first, but show great variation in more colloidal soils. The ratio values, however, are far from uniform, and exhibit little relationship.

The author is indebted to Prof. Hardy for his interest in this investigation, and his criticism of this paper.

V. Summary.

1. The value of the knowledge of the saturation capacity of a soil as an aid in its characterisation and classification is briefly stated.

2. A short account is given of the more important methods in use for determination of saturation capacity.

3. The theory underlying the method of Page and Williams, and the possible defects of the method are discussed.

4. The results of an investigation of this method lead to the following conclusions:

(*a*) Leaching the mixture of soil and calcium carbonate to 2 litres is insufficient to displace from the soil all its exchangeable bases.

(*b*) In view of this, it is recommended that 3 litres or more of filtrate be obtained, or preferably, the amount of soil employed be reduced to 10 grm.

(*c*) The leaching solution remains in contact with the soil mixture for a period adequate for the normal sodium chloride solution to be saturated with calcium carbonate.

(*d*) The difference in the amount of calcium, derived by solution from the carbonate, in the first and second litres of filtrate, is sufficiently small to be neglected.

(*e*) The tardiness with which the reaction proceeds to completion is probably due to the difficulty experienced in displacing the final amounts of adsorbed ions, rather than to the presence of calcium ions in the leaching solution.

(*f*) The incompleteness of the reaction renders the method of Hissink inaccurate for the calculation of the saturation capacity.

(*g*) The variation in the character of the colloidal material of soils is to some extent reflected in the value of the ratio of the calcium passing into solution through exchange reactions in the second litre, to that dissolved in this manner by the total volume of filtrate.

REFERENCES.

(1) BOBKO, B. W. and ASKINASI, D. L. (1925). "Die Methode zur Bestimmung der Absorptionskapazität." *Z. Pflanz. Düng.* A, **4**, 103.

(2) GEDROIZ, K. K. (1918). "Contribution to the Method of determining the Zeolitic Bases in the Soil." *Zhur. Opit. Agron.* **19**, 226. (Trans. Dr S. A. Waksman.)

(3) HENDRICK, J. and NEWLANDS, G. (1926). "Studies of a Scottish Drift Soil. Part IV." *Journ. Agric. Sci.* **16**, 584.

(4) HISSINK, D. J. (1925). "Base Exchange in Soils." *Trans. Faraday Soc.* **20**, 569.

(5) HISSINK, D. J. (1923). "Method for Estimating Absorbed Bases in Soils." *Soil Science*, **15**, 271.

(6) JOFFE, J. S. and MCLEAN, H. C. (1927). "Colloidal Behaviour in Soils and Soil Fertility. Part III." *Soil Science*, **23**, 127.

(7) PAGE, H. J. and WILLIAMS, W. (1925). "Studies on Base Exchange in Rothamsted Soils." *Trans. Faraday Soc.* **20**, 573.

(8) TJURIN, I. W. (1927). "Method of Determination of Exchangeable Calcium and Magnesium in Soils containing Alkaline Earth Carbonates." *La Pédologie*, **1**, 5.

(*Received December* 23*rd*, 1927.)

NUTRITIVE VALUE OF PASTURE.

III. THE INFLUENCE OF THE INTENSITY OF GRAZING ON THE COMPOSITION AND NUTRITIVE VALUE OF PASTURE HERBAGE (PART I).

By H. E. WOODMAN, M.A., Ph.D., D.Sc.,
D. B. NORMAN, B.A., and J. W. BEE, B.A.

(*The Institute for the Study of Animal Nutrition, School of Agriculture, Cambridge University.*)

Introduction.

In the first two publications of this series (1, 2), accounts have been given of investigations which were designed to secure information concerning the seasonal changes in the productivity, composition and nutritive value of pastures under conditions of close grazing. It was shown that under such conditions, a pasture will yield, irrespective of botanical composition, a herbage whose dry matter partakes of the nature of a protein concentrate of high digestibility and nutritive value. It was further demonstrated that the protein-rich and highly productive character of the herbage is retained over the whole season under a system of intensive grazing, especially when soil conditions, rainfall distribution and botanical composition combine to prevent a substantial diminution in the rate of growth on the pasture during the summer months. The significance of these findings in relation to the problems of grassland management was also fully gone into.

The keynote of the present investigation is furnished by the following quotation from the section of the 1927 paper (2) dealing with the question of supplementary feeding on pasture: "Might it not be possible, by a somewhat less severe system of grazing, to secure the herbage at a slightly more advanced stage of maturity, in which condition, whilst retaining the high digestibility and nutritive value of a concentrate, it will at the same time be better balanced in its content of protein and carbohydrate and be more adapted to meeting, in itself, the requirements of young stock and dairy animals?" It was in the hope of securing an answer, or partial answer, to this question, that these further trials were planned. The earlier experiments have, in effect, been repeated, the only difference being that the pasture plot was cut over

once per fortnight instead of once per week. Further investigations under still more lenient systems of cutting will be necessary before a complete answer can be given to the question stated above, as well as to the further question relating to the stage of maturity at which the nutritive value of the grass begins to run off.

GENERAL ARRANGEMENT OF INVESTIGATION.

The main trial during 1927 was carried out on the light-land pasture on which the 1925 experiment had been conducted. Detailed information concerning the earlier history of this pasture, the nature and composition of its soil and the botanical character of its herbage has been given in the publication dealing with the 1925 work (1). It is only necessary to add that basic slag, at the rate of 10 cwt. per acre, was applied to the pasture in the autumn following the conclusion of the 1925 investigation.

The pasture plot comprised 1·05 acres. This was divided into 14 equal sub-plots, each measuring $210 \times 35\frac{5}{7}$ links. Contiguous plots were also marked out for the purpose of hay and aftermath trials. During the winter prior to the experiment, the field had been grazed by four rams, so that the grass had been prevented from growing long and coarse. The usual preparation of the pasture plot, involving harrowing, rolling and removal of old winter grass, was accomplished during the March of 1927. Systematic cutting of the daily sub-plots was begun on March 21. By April 3, therefore, the whole plot had been cut over once, and from that date onward, the herbage obtained by the successive daily cutting of the sub-plots represented fortnight-old grass.

As in the earlier investigations, the grass, after cutting[1], was left as short as it might be left after being eaten down by sheep under conditions of heavy stocking. The conditions of the present trial, therefore, conformed roughly to such as would obtain under a system of sectional grazing, where the interval between two successive periods of grazing was of a fortnight's duration, and where, moreover, the enclosures, during every period of grazing, were so stocked as to ensure the fortnight's growth of herbage being grazed down very thoroughly.

In addition to the main experiment on the light-land pasture, a second trial was also carried out on the 1926 heavy-land pasture. At the conclusion of the 1926 investigation, this field had also been dressed

[1] It was found advisable to remove the front wooden rollers of the motor lawn-mower. When necessary to ensure satisfactory cutting of the fortnight's growth of grass, the machine was taken over the sub-plot twice.

with basic slag at the rate of 10 cwt. per acre, and sub-plots 2 and 3 had been fenced off for further experimental purposes. The sub-plots were prepared for the present season's work during the month of March. From the beginning of April until the end of September, sub-plot 3 was cut by means of the motor lawn-mower once per week, whilst sub-plot 2 was cut fortnightly. By this means, it became possible to compare, in the same season, the yield and composition of herbage under the two systems of cutting, and further, to ascertain how far weather conditions had been responsible for the remarkable differences between the curves of seasonal productivity obtained in 1925 and 1926 for the light-land and heavy-land pasture plots respectively (2).

It is not proposed in the present communication to bring forward detailed data respecting the seasonal changes of productivity of the two pastures and the relation of these to weather conditions and other influencing factors. It will be of obvious advantage to withhold such detailed discussion until the completion of this series of investigations, when data will have been accumulated which will render possible the treatment of the question of pasture productivity from the widest standpoint. In the present paper, only those yield data will be cited which bear directly on the nutritional aspects of the investigation. It will, however, be necessary to refer in general terms to the meteorological conditions which obtained during the season of the experiment, and for that reason, the monthly records are summarised in Table I.

Table I. *General meteorological conditions during the grazing season of* 1927.

Month	Apr.	May	June	July	Aug.	Sept.
Rainfall in inches	1·64	0·58	2·70	1·92	2·61	3·62
Average per day	0·055	0·019	0·090	0·062	0·084	0·121
No. of rainy days (0·01 in. or over)	14	8	18	17	20	20
Sunshine in hours	156	204	182	122	177	108
Average per day	5·2	6·6	6·1	4·0	5·7	3·6
No. of sunless days (1 hr. or less)	7	4	4	7	1	9
No. of absolutely sunless days	1	1	2	5	1	6
Mean max. daily temp. ° F.	54·7	62·8	64·7	68·3	70·3	62·4
Mean min. night temp. ° F.	39·3	42·8	46·5	52·6	53·0	48·3

A notable feature of the weather during the present season of experiment, and one which distinguished this season very sharply from the 1925 season, was the prevalence of droughty conditions during the early stages. May was a month of very low rainfall; indeed, the period from April 26 to May 14 was absolutely rainless. During 1925, on the other hand, the droughty part of the season extended from early June to mid-July, June being the month of lowest rainfall.

Botanical Notes.

As in previous investigations, careful surveys of the plots were made at different points of the season with a view to establishing the trend of the botanical changes in the character of the herbage. It is not essential, however, to give the results of these surveys in detail, since in the main the changes were very similar to those which were observed in the earlier investigations under the system of weekly cuts.

It is important to bear in mind, however, that the results of these experiments in respect of composition and nutritive value refer not merely to the grasses in the plots, but to the total herbage, including both weeds and grasses. In the early part of the 1927 season, for instance, it was computed that almost 20 per cent. of the herbage mown from the light-land pasture plot consisted of weeds like daisies, buttercups, dandelions and plantains; the proportion of weeds fell to about 10 per cent. in mid-season, but rose again during the later stages of the trial. It is conceivable, and indeed probable, that on pastures containing a lower proportion of weeds, even better results would have been obtained than those which have been recorded in the present series of investigations.

1925 *light-land pasture.* (*Season* 1927.) Up to the middle of July, *Lolium perenne* was the most prominent species in the pasture plot. During the second half of the season, however, this grass fell to the second place owing to the competition of *Agrostis alba*, which increased very much in amount in the final stages of the trial. *Poa trivialis* was prominent in the plot at all stages of the season with the exception of June, during which month the deleterious effect of the May and early June drought on the growth of this species was plainly discernible. Wild white clover displayed vigorous growth during June and July, though on the whole its development was not quite so conspicuous as was noted during 1925 under the system of weekly cutting. At its maximum phase of growth, it constituted about 15 per cent. of the mown herbage. For the rest, the botanical behaviour was very similar to that which was noted during 1925, and the reader is referred to the publication (1) dealing with the earlier work for fuller details concerning the different species of grasses and weeds which grew in the plot.

1926 *heavy-land pasture.* (*Sub-plots* 2 *and* 3.) As in the previous season's work, the main interest in respect of the growth of the grasses centred round the competition between *Poa trivialis* and *Agrostis alba*. The former grass figured prominently in the earliest stages of the season.

Its leaves, however, were very fine and slender, forming an almost continuous network of surface foliage, which did not contribute materially to the yield. As a whole, the grasses in this plot never attained, under the system of cutting, to the height reached by the rye-grass herbage of the light-land pasture plot. As the season progressed, *Agrostis alba* quickly advanced to the position of the dominant species in the sward, constituting about 60 per cent. of the total herbage at the end of June, at which time of the season *Lolium perenne*, *Dactylis glomerata*, *Poa trivialis* and *Cynosurus cristatus* together formed about 20 per cent.

The most striking feature, however, of the botanical changes in the heavy-land sub-plots during the present season of experiment lay in the behaviour of wild white clover. In the 1926 trial, the influence of the systematic cutting on the growth of this species, though quite noticeable, was not particularly outstanding. This was attributed at the time to the competition of creeping bent, which displayed very considerable growth and appeared thereby to react adversely on the productivity of the other species in the sward. At the conclusion of the experiment in autumn, the pasture plot, as well as the rest of the field (on which the aftermath, following hay-making, had not been grazed very efficiently) received a dressing of basic slag at the rate of 10 cwt. per acre.

During the spring of 1927, it was noted that wild white clover was beginning to display signs of vigorous activity, not only on the two sub-plots which were being cut, but also on the rest of the old experimental plot. This activity continued on such a marked scale, that during July it would have been possible to have marked out again the old pasture plot with the greatest accuracy by simply following the sharply-defined border of the flowering carpet of clover which covered the experimental area of the previous year. This very striking result was clearly a belated effect of the systematic cutting of the plot during 1926. Outside the line of clover flower, on the part of the field which had not been included in the 1926 trial, but which had, nevertheless, also been dressed with basic slag at the end of the experiment, it was a matter of difficulty to discover even individual plants of clover. It would appear, therefore, that the close grazing of pastures may lead to a much speedier stimulation of clover growth than is possible by slagging alone. The maximum effect will probably result when slagging is followed by more intensive grazing.

SEASONAL VARIATIONS IN THE CHEMICAL COMPOSITION OF THE PASTURE CUTS.

I. 1925 *Light-land Pasture Plot.* (*Season* 1927.)

The data obtained in the analysis of the various composite grass samples are summarised in Table II, which gives a continuous record of the composition of the fortnightly-cut grass from the beginning of April to the end of September. As in previous publications, corrections have been made for the soil content of the herbage, the net result of such corrections being to base the figures on a common silica content of 1·72 per cent. (1) The corrections were made on the assumption that the soil included in the grass samples consisted mainly of worm-casts, a sample of the latter showing, on analysis, the following composition on the basis of dry matter: Ash, 85 per cent.; CaO, 0·89 per cent.; P_2O_5, 0·27 per cent.; SiO_2, 81·09 per cent.

Table II. *Composition of soil-free samples of pasture grass from light-land pasture under system of fortnightly cuts (on basis of dry matter).*

Digestion period		1		2		3	
Date of cutting (1927)	Apr. 4–18	Apr. 19–May 2	May 3–9	May 10–23	May 24–June 4	June 5–16	June 17–July 4
	%	%	%	%	%	%	%
Crude protein	27·93	25·48	23·49	21·55	21·84	22·31	21·31
Ether extract	5·87	7·55	6·26	6·27	6·56	6·00	5·76
N-free extractives	42·75	43·46	46·46	47·34	45·79	46·53	47·61
Crude fibre	12·91	14·05	14·53	15·42	16·58	16·56	16·66
Ash	10·54	9·46	9·26	9·42	9·23	8·60	8·66
True protein	25·26	22·11	21·20	19·43	19·32	19·65	19·18
"Amides"	2·67	3·37	2·29	2·12	2·52	2·66	2·13
Lime (CaO)	1·29	1·44	1·41	1·42	1·50	1·42	1·56
Phosphate (P_2O_5)	1·15	1·17	1·15	1·06	1·06	1·01	1·03
Moisture as cut	77·20	79·00	78·10	78·30	75·50	72·50	74·70

Digestion period	4		5		6	
Date of cutting (1927)	July 5–18	July 19–Aug. 1	Aug. 2–15	Aug. 16–29	Aug. 30–Sept. 12–	Sept. 13–Oct. 2
	%	%	%	%	%	%
Crude protein	24·36	23·62	22·80	23·00	24·28	23·31
Ether extract	7·26	7·28	6·83	6·37	6·59	6·32
N-free extractives	41·67	41·97	43·90	43·69	43·00	44·67
Crude fibre	16·75	16·95	17·13	17·23	16·71	15·72
Ash	9·96	10·18	9·34	9·71	9·42	9·98
True protein	20·96	21·09	19·86	20·82	21·22	20·80
"Amides"	3·40	2·53	2·94	2·18	3·06	2·51
Lime (CaO)	1·68	1·62	1·61	1·61	1·54	1·41
Phosphate (P_2O_5)	1·17	1·22	1·22	1·23	1·29	1·26
Moisture as cut	79·80	79·20	78·20	77·40	77·40	76·10

Comments on Table II.

It is clear, from the data recorded in Table II, that the conclusions which were drawn respecting the composition of weekly-cut pasture

herbage hold also for grass grown under a system of fortnightly cuts. The dry matter of the fortnightly-cut grass is rich in crude protein and contains, in comparison with grass at the hay stage of maturity, a low percentage of crude fibre. Moreover, these characteristics are retained, by systematic cutting at fortnightly intervals, over the entire season.

It is of interest to compare the data obtained in the present trial with those obtained during the 1925 season on the same plot under the more drastic system of cutting. A detailed comparison of the two sets of results is shown in Table III.

Table III. *Showing comparison between composition of pasture grass from light-land pasture plot under weekly and fortnightly systems of cutting (dry matter basis).*

Season System of cutting	1925 Weekly				1927 Fortnightly			
	Extreme values			Mean value	Extreme values			Mean value
	%		%	%	%		%	%
Crude protein	21·20	to	27·92	24·74	21·31	to	27·93	23·48
Ether extract	4·72	,,	6·45	5·29	5·76	,,	7·55	6·53
N-free extractives	42·04	,,	52·11	44·79	41·67	,,	47·61	44·53
Crude fibre	12·33	,,	17·68	15·39	12·91	,,	17·23	15·94
SiO_2-free ash	7·26	,,	8·72	7·77*	6·88	,,	8·82	7·80
True protein	18·13	,,	23·85	20·95	19·18	,,	25·26	20·84
"Amides"	2·20	,,	5·62	3·79	2·12	,,	3·40	2·64
Lime (CaO)	1·23	,,	1·81	1·53	1·29	,,	1·68	1·50
Phosphate (P_2O_5)	0·87	,,	1·14	1·03	1·01	,,	1·29	1·15
Moisture as cut	69·0	,,	80·5	76·0	72·5	,,	79·8	77·2

* Omitting mineral figures for Period 10, 1925.

Table III reveals the fact that there is very little to distinguish the composition of the herbage obtained under the fortnightly system of cutting during 1927 from that of the weekly-cut herbage grown on the same pasture plot during 1925. The falling off in the percentage of crude protein was but slight and, indeed, is probably to be attributed to the somewhat less vigorous growth of wild white clover during 1927 than to any significant change in the composition of the grasses. Evidence will be brought forward later in this paper to show that wild white clover is, in its young stages, slightly richer in crude protein than grasses at a similar stage of maturity. It will be noted that the slight diminution in crude protein was due to the circumstance that the fortnightly-cut herbage was, on an average, somewhat poorer in non-protein nitrogenous substances than the weekly-cut grass, the content of true protein being almost identical in both types of herbage.

In respect of content of crude fibre, N-free extractives, SiO_2-free ash

and true protein, the data for the grass samples obtained under the two systems of cutting display great similarity. The only definite distinction in respect of organic composition is provided by the figures obtained for the percentages of ether extract, the more lenient system of cutting giving rise to a herbage which contained a definitely higher percentage of ether-soluble material. The mean value of 6·53 per cent. obtained for the fortnightly-cut grass compares very closely, however, with the mean value of 6·48 per cent. obtained for the weekly-cut herbage from the heavy-land pasture during 1926. It is probable that the amount of ether extract in pasture grass is affected more by differences in weather conditions than by slight differences in the system of cutting. It has already been demonstrated (1) that the digestibility, and presumably the chemical nature, of this constituent is affected in a more pronounced degree by seasonal alterations of meteorological conditions than is the case with any of the other constituents of pasture grass.

The average percentages of lime in the fortnightly and weekly-cut grass were almost identical, namely, 1·50 and 1·53 per cent. respectively. In respect of phosphate, the 1927 herbage was slightly richer than that of 1925. The somewhat lower mean moisture content of the weekly-cut herbage is to be attributed to the effect of the severe drought which characterised the 1925 summer period. Droughty conditions were also prevalent during May and early June in 1927, the influence of these conditions being clearly traceable in the seasonal values for the moisture content of the grass samples.

The same general features in respect of seasonal variations of composition, organic and inorganic, were displayed in both the 1925 and 1927 investigations. The percentage of crude protein showed a slight temporary falling off during mid-season, whereas the fibrous constituent gradually increased in amount during the summer period and fell off again in the later stages. In both seasons, the lime content of the grass attained to a maximum in July, the percentage of phosphate being at its lowest value in the summer period. In the case of the lime constituent, however, the range of seasonal variation was not so wide during the season of the present experiment as during 1925, though this difference is to be attributed rather to the less abundant growth of wild white clover than to the effect of the more lenient system of cutting.

II. 1926 *Heavy-land Pasture.* (*Sub-plots* 2 *and* 3.)

In Table IV are recorded the data for the composition of the grass samples obtained from the clay-land pasture sub-plots during the 1927

season under systems of weekly cutting (sub-plot 3) and fortnightly cutting (sub-plot 2). The figures represent the composition of the soil-free grass, being based on a common silica content of 1·48 per cent. (2) The data employed in the correction for the soil content of the grass samples were obtained from an analysis of a sample of worm-casts, the latter containing, on the basis of dry matter, 79·5 per cent. ash, 1·55 per cent. CaO, 0·31 per cent. P_2O_5 and 72·8 per cent. SiO_2. In order to economise time and labour, the grass samples were not analysed separately in every case, but were made up into composite samples as indicated in Table IV.

Table IV. *Composition of soil-free samples of pasture grass from heavy-land pasture under systems of weekly and fortnightly cuts (on basis of dry matter).*

Weekly Cuts. (Sub-plot 3.)

No. of cut	1	2	3, 4†, 5, 6	7, 8, 9, 10	11, 12, 13, 14	15, 16, 17, 18	19, 20, 21, 22	23, 24, 25, 26
Date of cutting (1927)	Apr. 4 —	Apr. 18* —	Apr. 25 May 2, 9, 16	May 23, 30 June 6, 13	June 20, 27 July 4, 11	July 18, 25 Aug. 1, 8	Aug. 15, 22, 29 Sept. 5	Sept. 12, 19, 26 Oct. 3
	%	%	%	%	%	%	%	%
Crude protein	25·71	25·85	23·96	24·45	26·45	30·74	29·96	27·86
Ether extract	6 31	7·91	8·02	6·52	6·84	7·39	6·62	6·28
N-free extractives	44·92	41·51	44·22	45·19	42·88	36·06	38·35	40·15
Crude fibre	15·44	14·01	14·19	14·40	14·42	15·89	14·81	14·58
Ash	7·62	10·69	9·61	9·44	9·41	9·92	10·23	11·13
True protein	21·96	22·64	20·79	21·02	22·81	26·11	25·51	24·27
"Amides"	3·75	3·21	3·17	3·43	3·64	4·63	4·45	3·59
Lime (CaO)	1·68	1·51	1·47	1·77	1·90	1·71	1·68	1·52
Phosphate (P_2O_5)	1·18	1·18	1·06	0·99	0·97	1·21	1·23	1·26
Moisture as cut	72·00	78·20	78·30	72·70	76·80	83·40	79·10	75·20

Represents a *fortnightly* cut. † Composite samples made up as indicated.

Fortnightly Cuts. (Sub-plot 2.)

No. of cut	1	2, 3†	4, 5	6, 7	8, 9	10, 11	12, 13
Date of cutting (1927)	Apr. 18* —	May 2, 16 —	May 30 June 13	June 27 July 11	July 25 Aug. 8	Aug. 22 Sept. 5	Sept. 19 Oct. 3
	%	%	%	%	%	%	%
Crude protein	24·74	22·76	22·73	24·94	28·01	28·41	25·35
Ether extract	7·16	6·85	5·27	6·78	7·84	7·50	6·29
N-free extractives	44·93	46·20	47·02	43·53	37·33	36·71	42·26
Crude fibre	14·27	14·74	15·33	15·60	17·03	16·91	15·43
Ash	8·90	9·45	9·65	9·15	9·79	10·47	10·67
True protein	21·08	19·58	19·47	21·29	22·96	23·68	21·45
"Amides"	3·66	3·18	3·26	3·65	5·05	4·73	3·90
Lime (CaO)	1·20	1·60	1·70	1·82	1·57	1·68	1·47
Phosphate (P_2O_5)	1·16	1·00	0·95	1·03	1·19	1·30	1·26
Moisture as cut	75·80	78·00	71·70	80·10	82·90	80·20	74·80

* Represents a *three weeks'* growth. † Composite samples made up as indicated.

Comments on Table IV.

A noteworthy feature of the results in Table IV is the unusually high percentage of crude protein in the weekly pasture cuts over the period

from July 11 to September 5. During the month July 11 to August 8, the dry matter of the grass contained 30·74 per cent. of this constituent, this being the highest value recorded so far in this series of investigations. The crude protein content of the weekly pasture cuts ranged from 23·96 to 30·74 per cent. of the dry matter, with a mean value for the whole season of 26·87 per cent. On the same pasture plot in the previous year, the content of crude protein in the weekly-cut herbage varied from 21·75 to 27·22 per cent., with a mean value of 24·74 per cent.

It has already been shown that the botanical conditions in the plot during 1926 and 1927 were not strictly comparable on account of the much stronger growth of wild white clover during the season of the present experiment. Since the surprisingly high crude protein figures for the weekly pasture cuts during July and August coincided with the period of maximum luxuriance of wild white clover, it would appear permissible to conclude that young clover actually contains a somewhat higher percentage of crude protein than young grass, although the latter, as has been abundantly demonstrated, is itself exceedingly rich in respect of this constituent. Even in the case of the fortnightly-cut herbage from sub-plot 2, higher percentages of crude protein were found during July and August than were recorded for any of the weekly pasture cuts from the same plot during 1926.

Table V. *Mean composition of weekly and fortnightly pasture cuts from heavy-land pasture,* 1927 (*on basis of dry matter*).

	Weekly cuts %	Fortnightly cuts %
Crude protein	26·87	25·28
Ether extract	6·99	6·81
N-free extractives	41·66	42·57
Crude fibre	14·73	15·61
Ash	9·75	9·73
True protein	23·14	21·36
"Amides"	3·73	3·92
Lime (CaO)	1·66	1·58
Phosphate (P_2O_5)	1·14	1·13

A further effect of the extraordinary development of wild white clover during 1927 was to raise the percentage of lime in the dry matter of the July weekly pasture cuts from 1·39 per cent. (1926) to 1·90 per cent. (1927). As with the weekly cuts, the maximum lime content of the fortnightly-cut grass, namely, 1·82 per cent., was reached during the period June 13 to July 11. During the rest of July and in August, the protein content attained to its highest value for both the weekly and fortnightly-cut herbage. On the other hand, the lime content,

instead of displaying a corresponding rise, fell off somewhat in both cases, a behaviour which suggests that wild white clover is richer in lime during the pre-flowering period than during the stage of flowering.

The differences in composition between the 1927 weekly and fortnightly cuts from the heavy-land pasture sub-plots are not very considerable, as will be seen from a study of the data in Tables IV and V.

The fortnightly-cut grass is slightly poorer in protein, and slightly richer in fibre, than the weekly-cut grass. In other respects, the two sets of analytical data display great similarity. Indeed, it is not improbable that the distinction in protein content was due mainly to inequalities of clover distribution over the experimental areas, since it was noted, long before the analytical work was carried out, that wild white clover grew somewhat more thickly on the weekly-cut sub-plot than on the sub-plot submitted to fortnightly cutting.

No purpose is to be gained by comparing the two sets of figures obtained for the moisture content of the grass samples as cut, since these values were obviously influenced in large measure by the weather conditions at the times of cutting the sub-plots.

A further feature of the figures in Table IV is worthy of notice. The first grass sample from sub-plot 2 represented a three weeks' growth of herbage. The results for this sample, however, were very similar to those obtained for the fortnightly cuts. It would appear possible, therefore, that little or no change in composition takes place during the course of three weeks' active growth. It would be unsafe at present, however, to attach too much significance to this single result, since the period of growth of this sample constituted the first three weeks of the early season (March 28 to April 18). It is conceivable that a different result might be obtained at a later stage of the grazing season.

The results of the trial carried out on the heavy-land pasture confirm the conclusions drawn from the light-land pasture experiment, namely, that in respect of chemical composition, there is little to distinguish pasture grass cut at fortnightly intervals from that obtained under a system of weekly cuts.

Seasonal Variations in the Nutritive Value of the Pasture Cuts.

With a view to securing information concerning the digestibility and nutritive value of the fortnightly-cut herbage, a succession of digestion trials with two pure-bred Suffolk wether sheep, aged about 13 months at the commencement of the trial, was carried out during the season.

The procedure adopted in such trials has been described fully in the first two publications of this series and therefore need not be dealt with in the present communication. Six digestion trials were made in all, the dates of these trials being shown in Table II. The daily ration of the sheep consisted of 4000 gm. of pasture grass in every period with the exception of period 3, when the ration was increased to 4400 gm. per day. During the intervals between periods, the animals were still kept on the experimental ration, but were taken out of the metabolism crates and given the run of out-door pens.

The mean results for the digestion coefficients of the pasture grass are summarised in Table VI. It is not necessary to tabulate the analytical results for the composite samples of faeces and grass, since these figures may readily be calculated from the data given in Appendix I, in which is recorded all the essential data relative to the digestion trials. The mean composition of the soil-free grass corresponding with the several digestion periods has already been given in Table II.

Table VI. *Summary of digestion coefficients.* (*Mean for two sheep.*)

Period	1	2	3	4	5	6
Mean date (1927)	Apr. 26	May 17	June 11	July 12	Aug. 9	Sept. 6
	%	%	%	%	%	%
Organic matter	82·3	81·4	78·6	78·0	78·3	79·3
Crude protein	81·7	79·3	78·8	79·2	79·5	80·7
Ether extract	66·0	59·2	52·7	54·6	53·7	51·9
N-free extractives	85·6	85·3	80·8	80·4	80·0	82·0
Crude fibre	82·1	81·1	81·3	80·3	82·3	81·1

Comments on Table VI.

It is of primary interest to inquire how far the conclusions respecting the digestibility of pasture herbage grown under a system of weekly cuts are tenable in the case of the fortnightly-cut herbage. A comparison of the digestion coefficients of the organic matter in the grass samples obtained under the two systems of cutting is shown in Table VII.

Table VII. *Digestion coefficients of organic matter of pasture cuts.*

Comparison of results obtained in 1925 and 1927 on light-land pasture.

Month	Apr.	May	June	July	Aug.	Sept.	Oct.
	%	%	%	%	%	%	%
1925 weekly cuts	83·4	83·6	80·7–77·4	74·0	74·4–75·8	79·7	80·7
1927 fortnightly cuts	82·3	81·4	78·6	78·0	78·3	79·3	—

An inspection of the data recorded in Table VII brings out the striking fact that there is very little difference between the digestibility of grass cut at weekly and at fortnightly intervals. For the April grass,

the digestion coefficients of the organic matter were 83·4 and 82·3 per cent. respectively. The difference between these values becomes devoid of significance when it is borne in mind that two different pairs of Suffolk wethers were employed in the 1925 and 1927 trials, and that even larger differences are frequently noted between the digestion coefficients for two sheep receiving the *same* ration.

Any differences which may be noted between the digestion coefficients of the grass during the summer periods are to be attributed mainly to the influence of the different sets of meteorological conditions which characterised the seasons of 1925 and 1927. It has already been demonstrated (1) that on pastures situated on such sandy soils, scantiness of rainfall exerts a depressing effect on both productivity and digestibility. During 1925, droughty conditions were encountered from the beginning of June up to mid-July, the influence of these conditions being observable in the marked falling-off of digestibility in the months of July and August. During 1927, however, May and early June constituted the dry part of the year, the rainfall during the rest of the season being very copious. The effect of the May drought on digestibility was not so marked as that of the June drought during 1925. The digestion coefficient of the grass never fell below the high value of 78 per cent. throughout the whole of the 1927 season. Obviously the power of recovery, under the influence of rain following drought, is greater during June than during July and August, this statement being equally true in respect of both digestibility and productivity. It is of further interest to note that the digestion coefficients of the fortnightly-cut and the weekly-cut grass during the final stages of the trials in September were practically identical.

The prevalence of droughty conditions during May, the month in which a zenith growth of grass normally prevails, is usually regarded as being prejudicial in a high degree to the yield and nutritive value of the season's growth in both meadow and pasture. In the case of hay, this is naturally true, since even when favourable meteorological conditions follow in June, the time during which the meadow can recover from the early set-back is of limited duration, especially in view of the fact that improvement in productivity and digestibility always lags behind an improvement in respect of rainfall. On poorly-managed pasture also, a droughty May will probably lead to a quicker falling-off of nutritive value than would be noted during a season of favourable meteorological conditions. Under a system of close-grazing, however, or where the herbage is eaten down thoroughly at short intervals, as in sectional grazing practice, a droughty May need not exert any marked

depressing effect on the digestibility of the herbage during the summer months, provided, of course, that adequate rainfall be registered during June and July. The truth of this statement is clearly brought out by the results of the present investigation.

Indeed, it is possible that an occasional dry spring followed by a favourable summer may actually be beneficial on such pastures as normally are not grazed closely. Scarcity of grass during the early part of the season leads to pastures being grazed more tightly than usual, the effect of this being manifested in the profuse display of wild white clover in the herbage during July. This effect was particularly noticeable in the Cambridge district during the season of 1927.

One outstanding effect of the droughty May weather was to lower in a remarkable manner the palatability of the pasture herbage. Little attention has up to the present been paid to the important question of palatability, the main interest in pasture grass having centred round yield, composition and nutritive value. Mention should be made, however, of certain valuable preliminary work which has been carried out by Stapledon and his co-workers at the Welsh Plant Breeding Station (3) on the effects of methods of grazing on the palatability of Italian rye-grass.

A large number of digestion trials on young pasture grass have now been carried out with different sheep in this Institute during the last three years. In only one instance have the animals shown any disinclination to consume the ration of grass. During period 3 (June 5 to June 16) of the present investigation, the mean dry matter of the grass as consumed rose to the high value of 31·84 per cent. as a consequence of the dry weather in the preceding weeks. It was further noted that the grass samples were beginning to contain an increasing proportion of dried stems of grasses which had died off during the period of drought. Nevertheless, the trial proceeded satisfactorily until the twelfth day of the period, when both animals suddenly refused to consume the grass ration. By no means (such as moistening the grass or mixing in a small proportion of maize meal) could they be induced to eat any portion of it, although, when tested later in the day, they ate readily of a ration composed of meadow hay and linseed cake. This particular digestion trial was therefore brought to a conclusion on the twelfth, instead of the fourteenth day, and the animals were taken off the grass diet for about a fortnight, by which time, under the influence of rain, the pasture herbage had regained its normal green and leafy appearance. It should be noted that the data obtained in this period for the composition and nutritive value of the grass presented no abnormal features. It must

be assumed therefore that the main effect of the droughty weather had been to render unpalatable a food which, under the usual conditions of growth, has always been found to be highly palatable. The observation should focus attention on the desirability of studying the pasture grass problem from the standpoint of palatability as well as of chemical composition.

Table VIII. *Digestion coefficients of crude protein of pasture cuts.*

Comparison of results obtained in 1925 and 1927 on light-land pasture.

Month	Apr. %	May %	June %	July %	Aug. %	Sept. %	Oct. %
1925 weekly cuts	79·3	85·4	81·1–78·4	77·1	76·6–78·9	83·4	84·0
1927 fortnightly cuts	81·7	79·3	78·8	79·2	79·5	80·7	—

The two sets of data in Table VIII for the protein digestion coefficients display, on the whole, a good degree of similarity, especially when allowance is made for: (1) The different meteorological conditions in the two seasons. The only discrepancy of any significant magnitude is that between the digestion coefficients of the protein in the May grass, the higher value for 1925 being probably due to the circumstance that the May of 1925 was a much better growing period than the May of 1927. The lower values for 1925 during July and August are again attributable to differences of weather conditions, the mid-season of that year being much droughtier than the corresponding period of 1927. (2) The fact that different pairs of animals were employed in the separate investigations. It must be borne in mind that the faeces of animals always contains nitrogenous material of a metabolic character, this leading to a depression of the true digestibility of the protein of the food. It may be that this "metabolic factor" did not operate equally in the two sets of trials.

It may be concluded that the fortnightly-cut grass, no less than the grass obtained by weekly cutting, is not only rich in respect of protein, but that its protein constituent is digested and utilised by animals to a very high degree.

Table IX. *Digestion coefficients of ether extract of pasture cuts.*

Comparison of results obtained in 1925 and 1927 on light-land pasture.

Month	Apr. %	May %	June %	July %	Aug. %	Sept. %	Oct. %
1925 weekly cuts	60·5	60·0	53·5–51·2	39·7	47·9–55·1	54·9	60·6
1927 fortnightly cuts	66·0	59·2	52·7	54·6	53·7	51·9	—

Table IX reveals a general similarity between the values for the digestion coefficients of the ether extract of the weekly and fortnightly-cut grass. The main difference is merely one of seasonal variation, the

prolonged drought during the mid-season of 1925 having led to a very pronounced temporary fall in the digestibility of the grass ether extract. It has already been shown that the only significant difference between the 1925 and 1927 grass samples in respect of chemical composition lay in the definitely higher percentage of ether-soluble material in the samples obtained under the more lenient system of cutting. The results shown in Table IX, however, suggest that this difference in amount of ether extract is probably unaccompanied by any essential difference in chemical nature.

Table X. *Digestion coefficients of N-free extractives of pasture cuts.*

Comparison of results obtained in 1925 and 1927 on light-land pasture.

Month	Apr.	May	June	July	Aug.	Sept.	Oct.
	%	%	%	%	%	%	%
1925 weekly cuts	88·1	87·4	81·6–78·5	75·0	76·0–77·4	79·9	81·6
1927 fortnightly cuts	85·6	85·3	80·8	80·4	80·0	82·0	—

It will be seen from Table X that the digestion coefficients of the N-free extractives of the 1927 fortnightly-cut herbage compare very favourably with the corresponding values for the 1925 weekly-cut grass. Indeed, during July, August and September, the 1927 values were actually higher than those for 1925. This difference, however, is solely to be ascribed to the influence of the droughty weather conditions which characterised the mid-season in the earlier year of experiment.

Table XI. *Digestion coefficients of crude fibre of pasture cuts.*

Comparison of results obtained in 1925 and 1927 on light-land pasture.

Month	Apr.	May	June	July	Aug.	Sept.	Oct.
	%	%	%	%	%	%	%
1925 weekly cuts	80·3	79·2	84·2–80·0	76·1	76·0–75·1	80·4	80·9
1927 fortnightly cuts	82·1	81·1	81·3	80·3	82·3	81·1	—

In attempting to decide whether the week-old grass undergoes any diminution in respect of digestibility during its second week of growth, the critical comparison is naturally that between the digestion coefficients of the fibrous constituents. The process in the plant which leads to a falling-off of digestibility is known as lignification, which results in the thin cellulose envelopes of the cells of the young plant becoming thickened by intimate admixture with the more carbonaceous lignocellulose. The cellulose constituent is a nutrient of high digestibility when consumed by ruminants; lignocellulose, on the other hand, is indigestible. The setting-in of the lignification process in the plant is accompanied not only by a falling-off in the digestibility of the fibrous constituent, but also by corresponding changes in the digestibility of the other plant

ingredients, since the latter become less accessible to the digestive ferments in the alimentary tract of the animal. It has already been shown that in respect of the digestibility of constituents other than fibre, the weekly and the fortnightly-cut grass display marked similarity. The data in Table XI show that this similarity extend also to the fibre digestion coefficients. There is no indication whatsoever of a diminution of fibre digestibility as a result of increasing the interval between successive cuttings from a week to a fortnight. It is clear that the fibre in the fortnightly-cut herbage still consists of the simple form of cellulose, and that it possesses a digestibility comparable with that of the soluble-carbohydrate fraction.

Table XII. *Amounts of digestible nutrients in dry matter of pasture cuts. Summary of starch equivalents and nutritive ratios.*

Period	1	2	3	4	5	6
Mean date (1927)	Apr. 26	May 17	June 11	July 12	Aug. 9	Sept. 6
	%	%	%	%	%	%
Dig. crude protein	20·82	17·09	17·58	19·29	18·13	19·59
Dig. ether extract	4·98	3·71	3·16	3·96	3·67	3·42
Dig. N-free extractives	37·20	40·38	37·60	33·50	35·12	35·26
Dig. crude fibre	11·54	12·51	13·46	13·45	14·10	13·55
Dig. organic matter	74·54	73·69	71·80	70·20	71·02	71·82
P.S.E. per 100 lb. dry matter (lb.)	73·75	71·56	68·83	67·79	68·31	69·00
Nutritive ratio	2·89	3·59	3·32	2·90	3·18	2·89

Table XIII. *Showing comparison between digestible composition of herbage from light-land pasture plot under weekly and fortnightly systems of cutting (on basis of dry matter).*

Season	1925			1927		
System of cutting	Weekly			Fortnightly		
	Extreme values		Mean value	Extreme values		Mean value
	%	%	%	%	%	%
Dig. crude protein	16·25 to	23·45	19·97	17·09 to	20·82	18·75
Dig. ether extract	1·96 „	3·55	2·87	3·16 „	4·98	3·81
Dig. N-free extractives	33·30 „	45·91	36·10	33·50 „	40·38	36·50
Dig. crude fibre	9·48 „	14·14	12·08	11·54 „	14·10	13·10
Dig. organic matter	66·89 „	75·59	71·02	70·20 „	74·54	72·16
P.S.E. per 100 lb. dry matter	62·08 „	73·70	67·74	67·79 „	73·75	69·87
Nutritive ratio	2·18 „	3·72	2·79	2·89 „	3·59	3·13

Comments on Tables XII and XIII.

From the data recorded in these tables, it may be concluded that the differences which may exist in respect of digestible composition, starch equivalent and nutritive ratio between pasture herbage obtained under weekly and fortnightly systems of cutting are not very considerable. Considering the average values for the whole season, the

fortnightly-cut grass appears to be slightly poorer in digestible protein, but definitely richer in digestible ether extract, than the weekly-cut grass. The content of digestible carbohydrate is approximately the same under both systems of cutting, while the small difference in respect of digestible fibre can scarcely be regarded as significant in the light of what is written below. The average values for the digestible organic matter and for the starch equivalent are actually slightly higher for the grass obtained under the more lenient system of cutting. Finally, the fortnightly-cut herbage possesses a slightly wider nutritive ratio than the grass cut at weekly intervals.

In seeking to trace the significance of these slight differences, it should be borne in mind that the values at any particular period of the season are influenced by the meteorological conditions in the immediately preceding period or periods. This is well illustrated by the seasonal changes of nutritive value during the 1925 season (1). Since the weather conditions in the two seasons of experiment were markedly different, and since, moreover, the growth of wild white clover in the plot during 1927 was not so prominent as in 1925, it is not improbable that such slight differences as are discernible between the two sets of data recorded in Table XIII are due to these considerations rather than to a direct effect of employing a somewhat more lenient system of cutting in 1927 than in 1925.

The results justify the conclusion that the dry matter of the pasture herbage grown under a system of fortnightly cutting is a protein concentrate equal in digestibility and nutritive value to that obtained by weekly cutting. There is no significant running-off in respect of composition and feeding value during the second week of growth. At the end of a fortnight, the herbage still consists of the same immature, non-lignified tissue as it was at the end of a week's growth. Since composition and nutritive value were maintained at a high level throughout the entire season under the system of fortnightly cuts, it may be inferred that similar results would follow from a system of sectional grazing, where the enclosures, after being thoroughly eaten down by stock, are permitted a fortnight's interval of unchecked growth before being grazed again.

NUTRITIVE RATIO OF FORTNIGHTLY-CUT GRASS.

Despite the slight widening of the nutritive ratio in the fortnightly-cut grass as compared with the weekly-cut herbage, the average value, namely, 3·13, is still significantly narrower than the nutritive ratio of

milk, namely, 4·2. The conclusions arrived at under the system of weekly cuts respecting the necessity for employing carbohydrate instead of protein concentrates for the purpose of supplementary feeding on closely-grazed pasture (1, 2) still hold good for pastures under a somewhat more lenient system of grazing.

The strict application of scientific standards to the feeding of pasturing animals is by no means a simple matter. It is, in the first place, difficult to ascertain the actual dry matter consumption of animals at grass, and assumptions have perforce to be made on this point. In the second place, when pasturage constitutes the *sole* diet, it cannot, at one and the same time, form a correctly balanced food for *all* classes of farm stock, nor even, indeed, for individual animals of varying milk-yielding capacity in the same dairy herd. Obviously, if the herbage possesses the correct balance for milk production, it must of necessity be unbalanced for fattening animals. In the case of well-managed grassland, the difficulty of feeding to scientific standards is apparent from a study of the data in Table XIV, in which are recorded the various requirements of certain typical farm animals, together with the amounts of starch equivalent and digestible protein such animals would actually consume if their diets consisted solely of young pasture herbage.

Table XIV. *Comparison of typical diets on well-managed pasture with scientific feeding standards.*

	Capacity for consumption, lb. dry matter per day	Scientific standards		Actually consumed on ration of young pasture grass	
		lb. starch equivalent	lb. digestible protein	lb. starch equivalent	lb. digestible protein
3-gallon cow	30	14	2·5	21·0	6·0
5-gallon cow	30	19	3·7	21·0	6·0
9-gallon cow	?	29	6·1	21·0*	6·0*
10 cwt. steer (beef production)	24	12·5	1·5	16·8	4·8
6 cwt. steer (for "baby beef")	17	9·2	1·4	11·9	3·4
13 cwt. steer (fattening)	28	15·9	1·8	19·6	5·6
100 lb. sheep (fattening)	3·5	2·2	0·25	2·5	0·7

* Assuming in this case a dry matter consumption of 30 lb.

Leaving out of account the extreme case of the 9-gallon cow, it will be seen from Table XIV that the pasture diet supplies in every case more starch equivalent than is actually required by the animals. Such surplus starch equivalent will partly be utilised for the muscular work performed by the animals in seeking their food on the pasture. The grass rations contain further an amount of digestible protein far in

excess of requirements. This is even true in the case of a dairy cow yielding as much as 5 gallons of milk daily. A ration of young pasture grass containing 30 lb. of dry matter includes almost sufficient digestible protein to meet the demands of a 9-gallon cow, although in this case the energy content of the ration is 8 lb. of starch equivalent below the standard amount. It is clear, however, that this extra starch equivalent should be supplied in the form of a supplement rich in digestible carbohydrate, and not in the form of protein-rich food.

Under what system of cutting, pasture grass will display the correct balance for any of the purposes indicated in Table XIV must be left for decision until this series of researches has been completed. So far as they have gone, however, the investigations have shown that pasture grass in its early stages of growth is not designed, on account of its high content of digestible protein, to produce the *optimum* results in farm animals not receiving some supplementary food richer in carbohydrate. By pursuing these investigations under more and more lenient systems of cutting, a stage may be reached where the balance between the protein and non-protein constituents in the grass corresponds roughly with that required by dairy cows yielding from 2 to 4 gallons of milk per day. At this stage, one part of digestible protein will be associated with five to six parts of starch equivalent in the grass, instead of with three and a half as in the young pasture grass. There is a danger, however, before such a stage is reached, that lignification of the grass will have set in, with consequent loss of the "concentrate" character.

The nutritive properties of closely-grazed pasturage can only be appreciated correctly by bearing in mind that such a fodder is essentially designed for productive purposes. If its dry matter is a protein concentrate, then it must be utilised like any other farm protein concentrate, if properly balanced rations are to be fed to animals in summer as well as in winter. This would, however, on pastures where the herbage is maintained in the young condition, imply restricted grazing and continuous supplementing to meet the needs of individual animals, an ideal system of intensive farming which naturally not many farmers would be prepared to adopt. At this stage, the writers are content to emphasise the desirability of employing carbohydrate-rich foods whenever supplementary feeding on well-grazed pastures is resorted to. The use of oil-cakes for this purpose serves merely to unbalance still further an already ill-balanced food.

Production of Nutrient Matter from Pasture Plots under Systems of Weekly and Fortnightly Cutting.

It is clear from the results of the present investigation that very little change occurs in the essential character of pasture herbage if the interval between successive cuts be increased from a week to a fortnight. After a fortnight's unchecked growth, however, there is a very significant increase in respect of the length and weight of grass on the pasture. Daily records were kept of the length of the week-old and fortnight-old grass on the sub-plots, though it is doubtful whether such data possess much real significance. The different species in the plot at any given date are so variable in height, that it is almost impossible to represent the height of the herbage by means of a single figure. Moreover, the height to which herbage is able to grow in a definite period on different pastures varies considerably, being influenced by such factors as botanical composition, habit of growth and climatic conditions. As an instance of this, it may be noted that the herbage of the 1926 heavy-land pasture plot never attained, under the same system of cutting, to the height reached by the grass on the 1925-1927 light-land plot, the habit of growth of the two kinds of herbage being very different.

The figures recorded in Table XV are therefore merely intended to give a rough idea of the average height reached by the "top grass" in the pasture plot of the present investigation. Their significance is restricted to the herbage of this pasture under the climatic conditions which prevailed in Cambridge during the season of 1927.

It may further be noted that many of the grasses, especially those possessing an early growth-period, were able, under the system of fortnightly cutting, to reach the early flowering stages. Flowering shoots of the following species were noted during the course of the experiment: meadow foxtail, soft brome grass, perennial rye-grass, rough-stalked meadow grass, tall oat-grass and burnet. Wild white clover flowered profusely, as did the weeds: buttercups, daisies and dandelions.

Table XV. *Height of "top grass" on light-land pasture plot during* 1927 *trial.*

Period of season	14 days after cutting inches	7 days after cutting inches
April	4–5	3
May	4	2¼
June	3	2
July	3½	2½
Aug. and Sept.	2½	1½

It is interesting to note from Table XV that during the spring the "top grass" grew to an average height of 4–5 inches, without, as is shown by the results of the digestion trials, any evidence of the setting-in of lignification.

Table XVI. *Production of nutrient matter from light-land pasture plot during* 1925 *and* 1927

Weekly cutting (Apr. 13 to Oct. 5, 1925)			Fortnightly cutting (Apr. 13 to Oct. 2, 1927)		
lb. dry matter per acre	lb. starch equivalent per acre	lb. digestible protein per acre	lb. dry matter per acre	lb. starch equivalent per acre	lb. digestible protein per acre
2833	1969	561	3621 =26·2 % increase	2532 =28·6 % increase	679 =21·0 % increase

The data in Table XVI show that, taking the yield per acre between corresponding dates of the two grazing seasons, the pasture plot produced a 26·2 per cent. bigger yield of dry matter in 1927 than in 1925. This result is of obvious significance in view of the fact that the nutritive value of the dry matter was equally good in both seasons. The improvement in 1927, however, is not wholly to be ascribed to the effect of the somewhat more lenient system of cutting, since the yield in any particular season may be influenced very profoundly by the prevailing meteorological conditions. The relative influences of weather and system of cutting may roughly be ascertained from the more detailed records given in Table XVII, which shows the yields of dry matter from the plot over corresponding periods of the two seasons.

Table XVII. *Seasonal yields of herbage from light-land pasture plot during* 1925 *and* 1927.

Period of season	Weekly cutting (1925) lb. dry matter per acre	Fortnightly cutting (1927) lb. dry matter per acre
Apr. 13 to May 25	1399	1337
May 26 „ July 27	794	1198
July 28 „ Sept. 28	567	1045

Table XVII reveals the interesting fact that, during the active spring growth period, the plot produced rather more dry matter per acre under the weekly system of cuts during 1925 than under the fortnightly system during 1927. This unexpected result is to be attributed to the particularly favourable meteorological conditions which characterised the month of May in 1925. During 1927, on the other hand, this month was very dry and the conditions, although not actually preventing a "zenith" period of growth on the plot at this date, were not favourable to such intensive activity as had been noted in the corresponding month of 1925.

During mid-season, the pasture plot produced much more heavily in 1927 than in 1925, a consequence of the combined effects of the more lenient system of cutting and the heavier rainfall during the summer of 1927.

The most significant difference, however, is the big disparity in yield from the plot during August and September of the two years of experiment, the yield during 1927 being nearly twice that obtained in 1925. This difference cannot be explained on the basis of differences of meteorological conditions in the actual periods under consideration, since although rather more rain fell during the August and September of 1927, yet the rainfall over the corresponding period of 1925 was entirely adequate for satisfactory growth.

The question therefore arises as to whether this notable difference in late-season productivity is to be correlated with the difference in the systems of cutting. This would, considered superficially, appear to be the case for the following reasons:

(1) It would be anticipated that the less intensive system, involving as it does the less frequent defoliation of the grasses, would result, other factors being equal, in the growth of a bigger weight of herbage. In other words, the more intensive the system of grazing or cutting, the smaller is the yield of grass likely to be, a statement which is supported by the results of Stapledon's grassland investigations at Aberystwyth (4).

(2) Sinclair (5) and Stapledon (4) have both noted that heavy grazing or drastic cutting during early spring leads to a lowering of the productivity of bulky early grasses like cocksfoot during the later part of the grazing year.

Before concluding, however, that the observed difference was actually due to a direct effect of employing a more lenient system of cutting, it will be advisable to consider the results which were obtained in the present investigation on the heavy-land pasture sub-plots, since in this case the question of comparative yield under weekly and fortnightly systems of cutting is answered more precisely. In the first place, the weather and soil conditions were the same for both plots, which adjoined each other. In the second place, the 1926 work had demonstrated that these sub-plots were remarkably comparable in respect of productivity, sub-plot 2, under the weekly system of cutting adopted during 1926, having yielded, between March 28 and October 24, 3690 lb. dry matter per acre, and sub-plot 3, 3710 lb. per acre. During 1927, sub-plot 2 was cut fortnightly and sub-plot 3 every week.

It will be seen from Table XVIII that although more dry matter

was produced under the more lenient system of cutting, the difference was much smaller than that noted between the total yields from the light-land pasture plot in 1925 and 1927, being only about 10 per cent. in favour of sub-plot 2 over the whole season. During the early period (March 29 to May 2) when, with the exception of the later days of April, the meteorological conditions were favourable for growth, the yields of dry matter from the two sub-plots did not differ by more than about 9·6 per cent.

Table XVIII. *Yields of dry matter from heavy-land sub-plots during* 1927.

Period of season	Sub-plot 2 (fortnightly cutting) lb. dry matter per acre	Sub-plot 3 (weekly cutting) lb. dry matter per acre
Mar. 29 to May 2	634·5	579·0
May 3 „ May 30	656·5	438·5
May 31 „ July 11	861·0	847·5
July 12 „ Oct. 3	1741·0	1670·0
Total (Mar. 29 to Oct. 3)	3893·0	3535·0

The difference, however, became very pronounced in the period May 3 to May 30, the sub-plot cut at fortnightly intervals producing during this time about 50 per cent. more dry matter than the weekly-cut sub-plot. It has already been pointed out that May was a month of very low rainfall, and conditions for growth were therefore not so favourable as is usual at this time of the season. With the improvement in rainfall which set in during the first week of June, the productivities of the two sub-plots levelled up remarkably, the more leniently cut sub-plot producing only 1·6 per cent. more dry matter during the period May 31 to July 11. From the latter date until the end of the trial on October 3, rainfall was copious, and the conditions for growth of grass were very satisfactory. Over this period, the yielding capacities of the two sub-plots were not very different, sub-plot 2 producing about 4·3 per cent. more dry matter than sub-plot 3. It will be noted that this last finding is in marked contrast to the result obtained on the light-land pasture plot, where the late-season production of dry matter under the fortnightly system of cutting during 1927 was nearly twice that recorded under the system of weekly cuts recorded during 1925.

The foregoing results are capable of being explained in the following way. Although intensification of the system of cutting tends to depress productivity, the difference between weekly and fortnightly systems is not sufficient to bring out this effect very prominently. When meteorological conditions are favourable to active growth of herbage, produc-

tivity under the two systems of cutting does not differ very greatly, certainly by not more than 10 per cent. in favour of the more lenient system. On the other hand, however, when meteorological conditions lead to a slowing-up in the rate of growth on the pasture (as during a spell of droughty weather) productivity under a system of cutting at fortnightly intervals becomes markedly higher than under a system of weekly cutting. It will be seen from the data in Table XVIII that this effect may be so pronounced as to bring about fundamental differences in the character of the curves of seasonal productivity for adjacent sub-plots submitted to weekly and fortnightly cutting respectively.

It still remains to account for the heavy production of dry matter on the light-land pasture plot during August and September of 1927 under the system of fortnightly cuts, as compared with the much smaller production on the same plot during the corresponding months of 1925 under the system of weekly cuts. Since the difference in the methods of cutting can only account for a small part of this big difference in productivity, it will be necessary to consider in greater detail the meteorological records of the two seasons.

During June and the first half of July in 1925, severe droughty conditions prevailed, and, as a consequence, productivity over a part of July fell almost to the zero level. It is probable, especially in view of the fact that, on such light-land pasture, improvement of yield has been shown normally to lag behind improvement in respect of rainfall, that the pasture never fully recovered from the effects of the prolonged summer drought, and that productivity remained at a sub-normal level for the remainder of the season. No such mid-season drought prevailed during 1927, and consequently the rate of growth of herbage during the later stages of the season was not depressed. The dry weather encountered during May appears to have had no measurable effect on the late-season productivity of the pasture plot, a fact which lends further emphasis to the statement made earlier in this communication, in connection with seasonal changes of digestibility, that the power of recovery of a systematically-grazed pasture, under the influence of rain following drought, is greater during June than during July and August.

To such considerations, therefore, and only in a minor degree to the effect of the different systems of cutting, must the observed difference in late-season productivity of the light-land pasture plot during 1925 and 1927 be attributed. It is proposed during the coming season of 1928 to submit the whole question to more detailed investigation by following the seasonal productivity of selected sub-plots on this pasture

under systems of weekly, fortnightly and 3-weekly cuts. At the present stage, however, it would appear that only when the systems of cutting vary more widely in intensity will the differences in yield, under ordinarily favourable weather conditions, become considerable. In the limiting case, when the herbage is permitted to grow unchecked for hay, and afterwards for a single late aftermath cut, it has been shown (1, 2) that the amount of dry matter so produced is roughly twice that obtained under a system of regular weekly cuts. In the present investigation on the light-land pasture, a hay cut (June 7) and an aftermath cut (October 3) together yielded 6364 lb. dry matter per acre as against 3796 lb. per acre from April 3 to October 2 by regular fortnightly cutting.

FURTHER SIGNIFICANCE OF RESULTS OF PRESENT INVESTIGATION.

The discovery of the protein-rich and highly digestible character of young grass led, in earlier publications (1, 2) to proposals for conserving a part of the produce of pastures (and, indeed, of lawns and sports-fields, where this is feasible) for use in winter as a protein-concentrated food. It was suggested that the preservation might be effected by artificial drying, followed, if it is desired to store the material over lengthy periods, by pressing into cakes, briquettes or nuts[1]. Alternatively, such young grass might be preserved by ensilage, either alone or in admixture with a carbohydrate-rich, absorbent feeding stuff like dried sugar beet pulp. It may be presumed that the latter method is more likely to find favour with the farmer in this country than the process involving artificial drying. Promising results have already been obtained in preliminary investigations into both these methods of preservation.

In the original proposals, it was assumed that it would be necessary to cut grass at weekly intervals in order to ensure that the preserved food should possess the character of a protein concentrate of high digestibility. With the completion of the present investigation, however, it has become clear that the same result can be achieved by cutting at fortnightly instead of weekly intervals. By modifying the procedure in this respect, not only will economy be effected in respect of labour, but bigger yields of herbage will also be secured for purposes of preservation. The desirability of continuing these investigations in the direction of ascertaining the effect of more lenient systems of cutting on the composition and nutritive value of pasture grass is obvious, both in respect

[1] In regions such as Australia, it might be desired to store such fodder-cakes over periods of years, for use in seasons of abnormal drought. Such dried, compressed cakes would be in a suitable form for long-distance transport.

of the possible bearing of the results on the question of the conservation of grass, and also in view of the fact that many farmers are now adopting the practice of sectional grazing, where the interval between successive grazings of pasture enclosures is usually about a month.

The results which have been obtained in the present investigation throw new light on the reasons for the very different curves of seasonal productivity which were obtained during 1925 and 1926, under a system of weekly cuts, on the light-land and heavy-land pasture plots respectively. This is a matter, however, which will be dealt with in a future publication dealing specifically with the factors which influence the productivity of pastures.

Summary.

The present investigation was undertaken with the object of ascertaining the effect of cutting at fortnightly instead of weekly intervals on the yield of pastures, and on the composition, digestibility and nutritive value of the herbage.

The main trial was carried out on the 1925 light-land pasture. The plot was divided into 14 sub-plots, and one sub-plot was mown per day. The whole plot, therefore, was cut over once per fortnight during the season. The results in respect of yield, composition and nutritive value were compared with corresponding results obtained on the same pasture plot under a system of weekly cuts during 1925.

A second trial was carried out on sub-plots 2 and 3 of the 1926 heavy-land pasture, one sub-plot being cut weekly and the other fortnightly. The work in this case was restricted to securing comparative data in respect of yield and composition of herbage.

The results from both trials lead to the conclusion that the differences in chemical composition, both organic and inorganic, between pasture grass cut at weekly and fortnightly intervals are inconsiderable. The dry matter of the fortnightly-cut grass is extremely rich in crude protein and contains, in comparison with grass cut at the hay stage of maturity, a low percentage of crude fibre. Moreover, these characteristics are retained, by systematic cutting at fortnightly intervals, over the entire season.

The results of the digestion trials justify the conclusion that the dry matter of the pasture herbage grown under a system of fortnightly cutting is a protein concentrate equal in digestibility and nutritive value to that obtained by weekly cutting. There is no significant running off in respect of composition and feeding value during the second week of

growth. At the end of a fortnight the herbage still consists of the same immature, non-lignified tissue as it was at the end of a week's growth.

Since composition, digestibility and nutritive value were maintained at a high level throughout the entire season under the system of fortnightly cuts, it may be inferred that similar results would follow from a system of sectional grazing, where the pasture enclosures, after being thoroughly eaten down by stock, are permitted a fortnight's interval of unchecked growth before being grazed again.

Despite the slight widening of the nutritive ratio in the fortnightly cut grass as compared with the weekly-cut herbage, the value is still significantly narrower than the nutritive ratio of milk. The conclusions arrived at under the system of weekly cuts respecting the desirability of employing carbohydrate instead of protein concentrates for the purpose of supplementary feeding on closely-grazed pasture still hold good for pastures under a somewhat more lenient system of grazing.

The light-land pasture plot produced 26 per cent. more dry matter, 29 per cent. more starch equivalent and 21 per cent. more digestible protein during the season of 1927 under the system of fortnightly cuts than during 1925 under the system of cutting at weekly intervals. The results obtained from the experiments on the heavy-land pasture subplots indicate, however, that this big improvement in productivity was not wholly to be ascribed to the employment of a more lenient system of cutting, but was partly due to the differences between the meteorological conditions which prevailed during the two seasons of experiment.

It was concluded that although intensification of the system of cutting tends to depress productivity, the difference between weekly and fortnightly systems is not sufficient to bring out this effect very prominently. When meteorological conditions are favourable to active growth of herbage, productivity under the two systems of cutting does not differ very greatly, certainly by not more than 10 per cent. in favour of the more lenient system. On the other hand, however, when meteorological conditions lead to a slowing-up in the rate of growth on the pasture (as during a spell of droughty weather) productivity under a system of cutting at fortnightly intervals becomes markedly higher than under a system of weekly cutting.

The significance of the results of the present investigation in relation to the problem of the conservation of young grass, either in the dried form or as silage, is discussed in the text.

The speedy stimulation of growth of wild white clover, which becomes possible by the adoption of a system of close-grazing, is again strikingly

illustrated by the results of systematic cutting on the heavy-land pasture plot. Evidence has been brought forward to show that wild white clover, in its young stages, is somewhat richer in crude protein than grasses at a similar stage of maturity.

An outstanding case of the lowering of the palatability of pasture herbage, as a result of droughty weather conditions, is described.

In conclusion, the writers gladly take this opportunity of acknowledging their indebtedness to Mr S. F. Armstrong, M.A., for generous assistance in connection with the botanical section of the work. Thanks are also due to Mr C. S. Leaf, B.A., for supplying the weather records, and to Prof. T. B. Wood, F.R.S. and Mr A. Amos, M.A., for the continuance of their interest in this series of investigations.

REFERENCES.

(1) Woodman, Blunt and Stewart (1926). *Journ. Agric. Sci.* **16**, 205.

(2) ——— (1927). *Journ. Agric. Sci.* **17**, 209.

(3) Stapledon, Fagan, Evans and Milton (1927). *Welsh Plant Breeding Station, Aberystwyth, Series H*, No. 5.

(4) Stapledon (1924). *Welsh Plant Breeding Station, Aberystwyth, Series H*, No. 3.

(5) Sinclair (1869). *Hortus Gramineus Woburnensis.*

(*Received December 23rd*, 1927.)

Appendix I. *Digestion Tables.*

Daily ration {4000 gm. pasture grass in Periods 1, 2, 4, 5 and 6.
{4400 gm. pasture grass in Period 3.

	Sheep V							Sheep VI						
	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extractives gm.	Crude fibre gm.	Ash gm.
***Period* 1**														
Daily ration	1083·60	943·17	265·48	78·67	452·73	146·29	140·43	1083·60	943·17	265·48	78·67	452·73	146·29	140·43
Food residues	30·00	12·00	3·36	1·00	5·78	1·86	18·00	34·00	15·00	4·20	1·25	7·23	2·32	19·00
Net consumption	1053·60	931·17	262·12	77·67	446·95	144·43	122·43	1049·60	928·17	261·28	77·42	445·50	143·97	121·43
Voided	246·20	164·73	47·44	27·28	64·31	25·70	81·47	242·80	163·84	48·22	25·42	64·39	25·81	78·96
Digested	807·40	766·44	214·68	50·39	382·64	118·73	40·96	806·80	764·33	213·06	52·00	381·11	118·16	42·47
Digestion coefficients (%)	76·63	82·32	81·90	64·88	85·61	82·21	33·45	76·87	82·35	81·55	67·17	85·55	82·07	34·97
***Period* 2**														
Daily ration	1029·60	926·33	220·33	64·15	484·12	157·73	103·27	1029·60	926·33	220·33	64·15	484·12	157·73	103·27
Food residues	4·80	2·80	0·67	0·19	1·46	0·48	2·00	4·70	2·70	0·64	0·19	1·41	0·46	2·00
Net consumption	1024·80	923·53	219·66	63·96	482·66	157·25	101·27	1024·90	923·63	219·69	63·96	482·71	157·27	101·27
Voided	226·40	169·05	44·35	24·63	70·80	29·27	57·35	232·90	175·05	46·63	27·55	70·71	30·16	57·85
Digested	798·40	754·48	175·31	39·33	411·86	127·98	43·92	792·00	748·58	173·06	36·41	412·00	127·11	43·42
Digestion coefficients (%)	77·91	81·70	79·81	61·50	85·33	81·39	43·37	77·28	81·05	78·78	56·93	85·35	80·82	42·88
Period* 3														
Consumed	1401·00	1245·91	304·16	81·54	634·37	225·84	155·09	—	—	—	—	—	—	—
Voided	355·60	267·06	64·51	38·55	121·72	42·28	88·54	—	—	—	—	—	—	—
Digested	1045·40	978·85	239·65	42·99	512·65	183·56	66·55	—	—	—	—	—	—	—
Digestion coefficients (%)	74·62	78·57	78·79	52·72	80·81	81·28	42·91	—	—	—	—	—	—	—
***Period* 4**														
Daily ration	894·00	748·55	202·49	60·35	346·42	139·29	145·45	894·00	748·55	202·49	60·35	346·42	139·29	145·45
Food residues	25·20	4·00	1·08	0·32	1·85	0·75	21·20	34·20	7·90	2·14	0·64	3·65	1·47	26·30
Net consumption	868·80	744·55	201·41	60·03	344·57	138·54	124·25	859·80	740·65	200·35	59·71	342·77	137·82	119·15
Voided	260·60	164·70	41·70	27·47	68·90	26·63	95·90	250·30	162·47	41·95	26·93	65·73	27·86	87·83
Digested	608·20	579·85	159·71	32·56	275·67	111·91	28·35	609·50	578·18	158·40	32·78	277·04	109·96	31·32
Digestion coefficients (%)	70·01	77·88	79·30	54·24	80·00	80·78	22·82	70·89	78·07	79·06	54·90	80·82	79·79	26·29
***Period* 5**														
Daily ration	992·00	877·82	220·72	66·16	425·08	165·86	114·18	992·00	877·82	220·72	66·16	425·08	165·86	114·18
Food residues	12·60	5·00	1·25	0·38	2·43	0·94	7·60	10·80	3·40	0·85	0·25	1·65	0·65	7·40
Net consumption	979·40	872·82	219·47	65·78	422·65	164·92	106·58	981·20	874·42	219·87	65·91	423·43	165·21	106·78
Voided	256·40	187·27	43·33	30·43	85·23	28·28	69·13	261·20	192·03	46·99	30·56	84·29	30·19	69·17
Digested	723·00	685·55	176·14	35·35	337·42	136·64	37·45	720·00	682·39	172·88	35·35	339·14	135·02	37·61
Digestion coefficients (%)	73·82	78·55	80·26	53·74	79·84	82·85	35·14	73·38	78·04	78·63	53·63	80·10	81·73	35·22
***Period* 6**														
Consumed	991·20	851·24	228·17	61·95	404·01	157·11	139·96	991·20	851·24	228·17	61·95	404·01	157·11	139·96
Voided	265·60	175·40	43·45	31·05	72·40	28·50	90·20	265·00	176·83	44·55	28·56	72·82	30·90	88·17
Digested	725·60	675·84	184·72	30·90	331·61	128·61	49·76	726·20	674·41	183·62	33·39	331·19	126·21	51·79
Digestion coefficients (%)	73·21	79·40	80·96	49·88	82·08	81·86	35·56	73·26	79·22	80·48	53·90	81·98	80·33	37·00

* Sheep VI not included in this period.

Note. The care of the experimental animals was in the hands of Messrs V. Thurlbourn and C. Bendall

APPENDIX II. *Showing Nitrogen, Lime and Phosphate Balances in Sheep during Digestion Trials.*

Mean daily nitrogen balances*.

	N consumed per day		N voided per day						Mean daily N balance	
			Urine		Faeces		Total			
	V	VI	V	VI	V	VI	V	VI	V	VI
Period	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
1	41·94	41·81	23·66	27·43	7·59	7·71	31·25	35·14	+10·69	+6·67
2	35·14	35·15	21·98	24·30	7·10	7·46	29·08	31·76	+ 6·06	+3·39
3	48·67	—	29·21	—	10·32	—	39·53	—	+ 9·14	—
4	32·23	32·06	21·15	24·26	6·67	6·71	27·82	30·97	+ 4·41	+1·09
5	35·11	35·18	24·25	26·35	6·93	7·52	31·18	33·87	+ 3·93	+1·31
6	36·50	36·50	23·46	26·63	6·96	7·13	30·42	33·76	+ 6·08	+2·74

Mean daily lime balances*.

	CaO consumed per day		CaO voided per day						Mean daily CaO balance	
			Urine		Faeces		Total			
	V	VI	V	VI	V	VI	V	VI	V	VI
Period	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
1	15·31	15·30	0·14	0·35	11·79	12·02	11·93	12·37	+ 3·38	+2·93
2	14·60	14·60	0·14	0·32	11·00	11·74	11·14	12·06	+ 3·46	+2·54
3	19·75	—	0·26	—	15·04	—	15·30	—	+ 4·45	—
4	14·35	14·29	0·21	0·28	11·18	11·14	11·39	11·42	+ 2·96	+2·87
5	15·79	15·79	0·23	0·26	13·46	13·95	13·69	14·21	+ 2·10	+1·58
6	14·97	14·97	0·20	0·25	13·52	12·85	13·72	13·10	+ 1·25	+1·87

Mean daily phosphate balances*.

	P_2O_5 consumed per day		P_2O_5 voided per day						Mean daily P_2O_5 balance	
			Urine		Faeces		Total			
	V	VI	V	VI	V	VI	V	VI	V	VI
Period	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
1	12·35	12·35	0·05	0·04	10·04	10·03	10·09	10·07	+ 2·26	+2·28
2	10·81	10·81	0·05	0·04	9·35	9·85	9·40	9·89	+ 1·41	+0·92
3	13·87	—	0·04	—	12·45	—	12·49	—	+ 1·38	—
4	9·85	9·83	0·05	0·04	8·47	8·71	8·52	8·75	+ 1·33	+1·08
5	11·88	11·88	0·03	0·03	11·18	10·89	11·21	10·92	+ 0·67	+0·96
6	12·29	12·29	0·04	0·03	11·71	11·47	11·75	11·50	+ 0·54	+0·79

* Allowance made for N, CaO and P_2O_5 in food residues.

APPENDIX III. *Showing Weight Changes in Sheep during Digestion Trials*.*

	V		VI	
	st.	lb.	st.	lb.
Initial weight (Apr. 15)	7	10	7	6
Final weight (Sept. 12)	9	6	9	0

At one or two stages of the season, the animals were taken off the experimental ration for a few days, so that the gains of live-weight were not entirely due to the effects of the grass diet.

CORRELATION OF YIELD IN OATS WITH METEOROLOGICAL OBSERVATIONS AT THE UNIVERSITY COLLEGE FARM, BANGOR, FOR THE PERIOD 1903–1926.

By R. ALUN ROBERTS, Ph.D.
(Department of Agriculture, University College, Bangor, N. Wales.)

(With One Text-figure.)

Introduction.

The fact that the findings of various workers on the influence of weather on yield in oats are seldom in agreement on all essential points suggests that the requirements of the crop varies from province to province, and warrants investigation within regions of relatively narrow compass.

The data for this paper is drawn from the oat variety trials of the University College Farm at Aber, near Bangor, from 1903 to 1926. The soil here is a stony heavy loam, mainly derived from local glacial drift of shaly character, overlying northern boulder clay. There is, besides, a certain amount of hill wash since the lowland is a narrow strip between steep foothills and the sea.

The climate is typical of the western sea board. January temperatures average from 41–42° F. and average July temperatures range about 60° F. The accumulated degrees of temperature below 41° for the winter months is only just above the figure for Penzance. The area is characterised by early springs with characteristic checks to the flush of growth in April or May due to drying east winds. The district is further characterised by high August rainfalls. Oats are put in generally in April and no harmful effects have been observed from sowing even in May. Sowing is general on the low ground in the latter half of August.

The plots are laid down in duplicate and vary in size from one-twelfth to one-sixth of an acre and every effort is made to obtain uniform soil conditions for the whole area. Since 1919 attempts have been made annually to secure the sowing of the same number of seeds (2·5 millions) per acre of each variety. Neglect of this fact, having regard to the variation in size and density of the seed grain, often accounts for thin crops and unsatisfactory results with new varieties. New seed is sown each year and as far as is possible this is obtained direct from the raisers of the variety.

The plots are cut separately as they mature and ripeness is determined in each case by the disappearance of the last tinge of green from the paleae. The varieties are generally threshed straight from the fields. The whole crop from a plot is weighed as it comes into the yard, the grain weight is determined, and the difference between this and the initial gross weight taken as weight of straw and chaff.

Data for yield are available for 16 years, and in all a very large number of varieties has been tested. The data available are all the more valuable and there is a high degree of continuity to the series because Abundance (white), Black Tartarian (black) and Goldfinder (yellow) have been grown for 12, 15 and 16 years respectively.

Note. No adjustment of yields is made (nor could be made as far as the writer can see) for the fact that the location of the trial plots changed yearly from field to field. The results are given with this reservation which must needs qualify all field tests. In the words of F. L. Engledow and G. Udny Yule (1 *a*) "a firm agricultural reservation must always be attached to yield trial results. The results of any trials are valid only for the precise cultural, soil and climatic conditions of those trials." Furthermore the writer is aware that 16 years form but an inadequate period of observation for such a study on statistical lines. It is hoped, however, that the tentative findings put forward will justify the work in that they have pointed to, and defined, critical factors which can be observed more closely in future years.

Historical.

The problem is of such complexity as warrants a somewhat detailed survey of previous work on the subject particularly where reference to such work appears later in the text.

R. H. Hooker (1) states that "oats like barley urgently require a cool summer, but they differ from barley in requiring rain in the spring. For the spring season the coefficient with rainfall is $-0{\cdot}69$. Before harvest (25th–32nd week), however, they would seem to like dry weather." Relating to work done at Rothamsted (2) on wheat and barley the following extract is of interest: "Of the various climatic factors affecting wheat rainfall is the most important single one accounting for some 30–40 per cent. of the whole climatic effects." The work of Martin G. Jones (3) at Aberystwyth for the six years 1920–5, as summarised in the Ministry of Agriculture's monthly weather reports, shows that various types of oats respond very differently to the same seasonal conditions owing to their being in different growth stages when certain weather conditions

prevail. Oat plants are more responsive to the weather conditions at certain critical stages than at other periods, and certain varieties are able to develop their normal grain under much colder conditions than others. As an insurance against adverse weather conditions at the time of heading and ripening he advocates the growing of different types of oats in preference to varying the dates of sowing.

Brounoff (4) found that in Russia the critical period for oats in respect to moisture is within the 10-day period before heading. Oats were seeded in his investigation early in April, headed the last of June and were harvested the last of July. An abundance of moisture was found necessary in June "when the oats plants are ready to develop a great number of new important vegetative organs." He states that hot days with mean daily temperatures above 75° and with maximum temperatures above 86° between the "earing" and the milk stage endangered the yield of oats, especially if there were a number of such days in succession. He found further that a similar temperature after the milk stage may cause a falling off of the grain.

In Germany a number of workers have given attention to this question. Bunger (5) found that soil moisture up to the time of grain formation had great significance. The richer the soil the greater is the injury that comes through lack of water. Straw yield is greatest on rich and well-watered soil, and, as yield of straw is already determined at flowering time, shortage of water after this period has no harmful effect on the yield of straw. He found that excess of water after the flowering period can, however, contribute to growth by the formation of tillers. The setting in of a dry period he found most harmful at the time of flowering and the beginning of grain formation, and the more favourable were conditions at the start, thereby forming ample ears and grain, the more accentuated the effect of drought at this period.

Blaschke (6) defines the ideal conditions for the various vegetative phases of oats as follows:

For seeding and after—rich winter moisture and sufficient warmth.

For shooting—moist warm cloudy weather.

For flowering—abundance of soil moisture with clear sunny weather.

For ripening—moderate moisture, warm and sunny.

Von Seelhorst (7) found that for oats a marked need of water comes at the end of May and the beginning of June and after that it quickly increases. The oat yield is dependent on soil moisture to the time of shooting. The need for water is much more influenced by temperature than is assimilation. At the time of the greatest increase of dry matter,

the plant needs water the least, whilst the relatively greatest need of water coincides with the smallest increase of dry matter.

The work of Walther Brouwer (8) at Gottingen is of a considerable direct interest to the present work, and, as it defines the conditions ruling over the conduct of the experiments, it gives us a good basis of comparison between inland continental areas and our own western maritime parts. The 23 years from 1900–1922 are examined in detail and the area is one of considerably less rainfall than Bangor's, with much wider temperature extremes from winter cold to summer heat.

He finds positive correlations for moisture and yield of oats at all stages of growth in the plant, showing that oats are favoured by moisture. The value of the correlation coefficients, however, are never big enough to show a high significance. The distribution of rainfall is shown to be more important than the total amount, and small rainfalls up to shooting have always given a bad crop. Moisture at flowering time or at ripening was found to have no influence on yield and Brouwer suggests that this is due to the fact that by flowering the plant has taken up the water and nutrients that it wants. He found, however, that temperatures proved more significant, and shows a marked correlation between temperature and oat yields in the period when the crop is covering the ground. The correlation is, in all cases, a negative one. Increase of temperature whether measured by maximum, minimum, or average temperatures results in a decreased crop and vice versa.

He maintains further that three weeks after the emergence of the shoots through the ground the yield has already been determined. Brouwer further maintains the necessity of long vegetative periods for good yields in oats together with early sowing. Sunshine, as a light factor, he finds unimportant and it can be regarded as a reflection of rain and temperature.

In the parallel case of barley Brouwer finds in the 20 days after appearance above ground the minimum temperature should be as low as possible. As this cardinal point of the need of high rainfall and low temperatures in the early stages is at complete variance with the Bangor results on oats and the Irish results of Dr Herbert Hunter (9) on barley his findings will be next considered.

Dr Herbert Hunter (9). Discussing climatic conditions in relation to the growth of barley, Hunter dwells on the need of a dry seed bed in the first stage when the plant is covering the ground and concentrating on root development. He quotes Sir A. D. Hall (10) on the difference of wheat yields in 1903, with its waterlogged winter condition, and 1904

with dry winter in which the plants had dry conditions for roots to rummage for food and to develop.

The earlier work of Seelhorst had already demonstrated the need of fairly dry conditions for successful root growth. Hunter regards a fully developed root system the fundamental requisite of high yield especially with reference to spring sown cereals which carry on growth and seed elaboration in approximately half the time occupied by wheat.

In conclusion Hunter remarks that "the effect of the climate is very complex and any effort to analyse its influence must receive detailed direction. Thus the figure of total rainfall and of total sunshine for any year are of limited use unless it is possible to correlate them with definite stages in the growth and the development of the plant and with its actual requirements in any direction and at any time."

American references are mostly quoted from J. Warren Smith (11) and are limited to the more important oat growing areas. The highest coefficient for the whole State of Ohio is for a cool June, with a wet June and July. For separate counties within the State various finer correlations are obtained. High April and May temperatures enhance the yield considerably in Wood County, whilst in Portage County, Ohio, a warm April and a cool and wet June are the conditions most favourable for oats.

In Indiana, a moderately wet May with a cool June gives the best yield, whilst in Illinois in a scrutiny of over 60 years high-yields are correlated with cool and wet Junes. April is the proved important "weather" month for oats in Iowa. Yield is concomitant with a warm and dry April and as sowing is general in the State of Iowa in early April, this indicates the importance of a good seed bed. The results show also some evidence that the temperature in June and July should be slightly below the normal for the best yield of oats.

In Maryland seed formation of spring oats is prevented in some parts if there is hot humid weather at heading time.

In North Dakota, in a review of 23 years in succession from 1892–1915, it was found that whenever June was warm and dry the yield of oats was below the normal in every instance, and when cool and wet the yield was above the normal 90 per cent. of the time. Similarly in Wisconsin oat yields correlate with a warm dry April and a cool wet June.

In conclusion, it is a general rule of wide application over the oat growing areas in the U.S.A. that "the temperature should be above the average for the season and locality and the precipitation below the

normal to produce the best conditions for seeding and the germination of the grain.

While the heads are forming, however, and the grain being developed, the crop must have cool and moderately wet weather to produce the best yields. Cool weather favours the ripening of the grain, while the crop is often materially reduced by a few hot days when it is near maturity."

Method of Procedure and Examination of Data.

Yield data. Between 1903 and 1926, we have exact yield data, grain and straw, for 17 years. In all 56 varieties have been grown, 38 white, 12 black, and 6 yellow. Yield of total grain is given in bushels of 42 lb., while straw and chaff are collectively reckoned in hundredweights.

Table I. *Yield in bushels to the acre.*

Black Black Tartarian	Yellow Goldfinder	White Abundance	Bushels per acre	Av. of all varieties	Av. of white varieties	Av. of yellow varieties	Av. of black varieties
—	101 1909	108 1909	Above 100	—	102 1909	101 1909	—
—	—	94 1907	100	94·6 1909	94 1907	—	—
—	—	—	to	90·0 1907	90 1916	—	—
—	—	—	90	—	90 1925	—	—
87 1909	89¼ 1919	—	90	89·3 1916	84 1914	85 1925	89 1909
87 1907	88 1925	—	to	85·0 1925	80 1922	84 1919	87¼ 1916
—	85¼ 1914	—	80	80·7 1914	—	—	84 1907
—	81 1907	—		—	—	—	80¼ 1914
74 1904	71¾ 1923	79½ 1914	80	74·5 1919	79¼ 1923	77 1907	79½ 1925
71¾ 1914	71 1911	74 1908	to	74·0 1923	73 1915	73½ 1914	73½ 1919
—	70 1904	—	70	72·0 1908	72¾ 1919	71 1911	—
—	—	—		70·6 1915	72½ 1908	71 1923	—
—	—	—		—	72 1926	—	—
68¾ 1925	68 1908	66 1911	70	66·7 1926	68¼ 1921	69 1904	69½ 1923
68¾ 1919	87¾ 1915	64½ 1921	to	64·8 1921	—	68 1908	69 1904
65¾ 1923	64¾ 1926	61¼ 1915	60	64·6 1922	—	68 1915	68 1908
63 1915	62½ 1922	—		63·0 1904	—	65½ 1922	68 1915
—	60¼ 1921	—		60·9 1911	—	63 1926	65¼ 1926
—	—	—		—	—	62 1921	62½ 1911
59 1908	52½ 1903	58¾ 1922	60	55·0 1903	59 1911	50½ 1903	55½ 1921
59 1926	—	56 1904	to	—	58¾ 1904	—	51 1922
58 1921	—	—	50	—	50¼ 1906	—	—
51¾ 1922	—	—		—	—	—	—
44 1905	—	46 1906	50	49·0 1905	47 1905	—	40½ 1905
—	—	45 1905	to	46·0 1906	40½ 1903	—	40 1906
—	—	43 1903	40	—	—	—	—
38¼ 1903	38 1906	—	40	—	—	39 1905	38½ 1903
31 1906	36 1905	—	to	—	—	38 1906	—
			30				
Av. = 62·0	Av. = 69·0	Av. = 65·5		Av. = 70·6	Av. = 73·0	Av. = 68·0	Av. = 66·0

The years are arbitrarily divided into groups on the basis of 10 bushels intervals in the yield, thus giving one a rough representation of the relative status of each variety or group of varieties. It is a significant

fact that with a few substitutions from column to column in Table I the run of the years is substantially the same. Further scrutiny establishes this and warrants the treatment of the effect of season on oat yield as a problem, to a large degree, dissociated from considerations of variety and type. The parallel rise or fall in yield, from year to year, of the single varieties or of the groups of varieties, with the respective rise or fall in yield of the average of all varieties is very close and very marked. Minor deviations from alignment will be treated separately further in the text, but the uniformity here exhibited stresses the fact that the question of seasonal variation in yield is of such dimensions as not to be marked in any appreciable degree by variations from year to year in the personnel of the oat varieties that chanced to be grown.

On this basis, for the rest of this section of the work, varieties will be treated collectively as a group of similars, and the yield figures for each and any year refer to the average yield of all varieties grown in that year.

The years 1909, 1907, 1916, 1925 and 1914 have proved in all cases seasons of high yield, while 1906, 1905 and 1903 have given yields far below the average; 1911, 1904, 1921 and 1922 have also been unsatisfactory for oats at Aber.

METEOROLOGICAL DATA.

The crude data worked on are, on the one hand, daily maximum and minimum air temperatures in degrees Fahrenheit as registered by thermometers in standard shelters, and on the other hand, rainfall in inches as registered at 24-hour intervals in a standard gauge openly exposed.

The records available for the College Farm cover but a part of the years under discussion. The records for Penrhyn Castle, three miles distant, are, however, complete and cover all the years in question. As there is almost complete agreement between the data from the two sources for the years covered by both, the figures used throughout are drawn exclusively from the Penrhyn Castle record.

Accumulated temperatures. The influence of temperature has been assessed by accumulating day degrees above "zero" of vital temperature. This zero of vital temperatures below which plants make little or no growth, according to Kincer (12), should be for spring sown crops, the mean daily temperature at the average date of the beginning of sowing for any locality. For this work, as elsewhere, zero temperature for oats has been taken as 42° F. The accumulated effective tempera-

			1903	1904	1905	1906	1907	1908	1909	1911	1914	1915	1916	1919	1921	1922	1923	1925	1926	Average
Apr.	1– 7	14	0·93	0·87	1·31	—	0·56	0·18	0·07	0·06	0·37	0·99	0·33	—	0·09	1·08	0·52	0·42	0·49	0·49
,,	8–14	15	0·33	0·82	0·39	0·24	0·36	0·40	0·66	—	0·29	0·70	0·81	0·51	1·00	1·37	1·06	0·51	0·05	0·56
,,	15–21	16	0·26	0·38	0·12	0·49	0·13	0·50	0·79	1·76	0·09	0·61	1·24	0·27	0·67	0·39	0·01	0·96	1·06	0·57
,,	22–28	17	0·14	1·71	0·75	0·98	0·57	1·29	1·21	1·25	0·03	—	0·08	0·57	0·07	0·66	0·35	0·22	0·12	0·59
,,	29–May 5	18	1·11	0·53	0·76	0·45	1·03	0·93	0·10	1·43	0·66	1·04	1·17	0·93	0·48	0·38	0·80	0·43	1·14	0·79
May	6–12	19	0·37	1·43	0·41	1·66	0·55	1·10	0·06	0·40	0·96	0·44	0·19	0·04	0·21	—	1·32	0·91	1·57	0·68
,,	13–19	20	0·78	0·80	—	0·61	0·04	0·24	0·21	—	—	0·81	0·71	0·18	0·69	0·45	0·60	0·99	—	0·42
,,	20–26	21	0·06	0·52	0·21	1·45	0·19	0·28	0·45	0·37	0·11	—	0·20	0·23	0·39	0·16	1·26	1·14	0·06	0·42
,,	27–June 2	22	0·08	1·01	0·21	0·59	1·01	1·00	0·46	0·03	0·09	0·04	—	—	0·32	—	0·13	0·82	0·49	0·37
June	3– 9	23	0·20	0·76	0·07	—	1·25	0·36	0·04	—	1·36	0·40	1·14	0·47	0·10	0·04	0·44	—	1·34	0·47
,,	10–16	24	0·58	0·74	0·46	0·16	0·87	2·53	—	0·51	0·55	—	0·48	0·50	0·04	0·56	0·43	0·07	1·35	0·58
,,	17–23	25	0·60	0·40	0·98	0·40	2·32	0·13	0·77	1·64	0·59	0·49	0·21	0·67	0·12	0·64	0·16	0·01	0·10	0·60
,,	24–30	26	0·66	0·32	0·28	1·45	0·32	—	1·14	0·80	0·75	0·22	0·70	0·78	0·08	0·87	0·33	—	—	0·51
July	1– 7	27	0·24	0·49	0·16	0·10	0·70	0·38	0·78	0·03	1·02	1·33	0·83	0·49	—	2·01	0·50	0·50	0·57	0·59
,,	8–14	28	1·01	0·25	0·60	0·28	0·40	1·84	1·24	0·03	0·43	0·12	0·72	0·63	1·00	0·21	0·11	0·17	0·26	0·55
,,	15–21	29	1·98	0·40	0·38	0·23	0·08	0·74	0·51	0·29	0·44	0·91	0·10	0·95	0·33	0·75	0·42	0·75	1·77	0·65
,,	22–28	30	0·86	1·02	1·70	0·30	0·87	0·39	1·34	0·38	0·46	0·96	—	—	1·17	0·64	1·77	1·14	0·40	0·78
,,	29–Aug. 4	31	1·23	0·69	0·57	1·85	0·24	0·05	0·44	1·85	0·60	0·68	—	0·52	3·72	0·45	0·32	0·55	0·23	0·86
Aug.	5–11	32	0·42	0·51	1·04	1·05	2·15	0·29	0·14	0·35	0·82	1·53	0·02	—	1·12	0·55	0·70	1·25	1·72	0·83
,,	12–18	33	2·05	1·44	0·30	1·02	1·14	0·89	1·50	0·45	—	0·19	1·77	1·66	0·58	0·90	1·14	0·72	0·80	0·86
,,	19–25	34	0·96	1·28	1·90	1·46	0·21	2·13	0·87	0·73	0·61	—	0·27	1·31	0·27	0·72	0·63	0·43	0·72	0·82
,,	26–Sept. 1	35	1·84	0·25	0·98	—	1·04	1·35	0·46	0·63	0·61	0·79	0·01	2·39	0·60	0·99	0·43	0·38	0·68	0·78

Table III. *Accumulated temperatures in day degrees (F.), corrected for Van't Hoff's law.*

			1903	1904	1905	1906	1907	1908	1909	1911	1914	1915	1916	1919	1921	1922	1923	1925	1926	Mean
Apr.	1– 7	14	36	31	25	32	33	15	22	3	47	31	—	24	39	—	39	27	121	30·9
,,	8–14	15	30	42	53	38	14	24	50	23	40	44	—	26	21	1	19	51	59	32·9
,,	15–21	16	3	61	21	28	27	15	56	61	100	40	—	51	14	6	53	29	34	36·0
,,	22–28	17	31	54	68	8	55	26	69	59	101	68	113	19	45	12	51	29	42	50·1
,,	29–May 5	18	77	74	48	56	53	119	64	61	96	63	184	55	45	24	105	43	92	72·7
May	6–12	19	50	45	69	86	126	84	90	118	52	87	175	119	118	81	40	65	34	84·3
,,	13–19	20	56	107	99	46	57	116	49	120	148	75	100	172	68	40	37	117	33	85·9
,,	20–26	21	135	92	72	94	86	105	164	131	88	135	56	188	103	123	76	125	140	114·6
,,	27–June 2	22	147	136	165	121	105	180	130	228	117	96	129	179	62	169	65	94	114	132·1
June	3– 9	23	114	191	165	191	125	123	175	107	190	123	142	130	152	133	133	104	177	143·6
,,	10–16	24	103	142	191	157	131	107	114	136	166	184	161	188	124	132	102	193	116	145·9
,,	17–23	25	108	155	197	211	122	124	142	149	158	152	178	145	154	123	158	112	171	152·0
,,	24–30	26	204	142	242	139	107	252	107	124	214	178	172	134	205	92	138	144	116	160·4
July	1– 7	27	171	168	182	166	111	233	157	187	186	180	137	132	181	112	275	149	200	170·2
,,	8–14	28	199	200	260	146	157	168	162	229	238	150	163	161	290	112	264	167	270	194·4
,,	15–21	29	173	236	213	204	244	150	176	236	217	150	187	182	283	143	184	216	281	201·7
,,	22–28	30	172	219	197	210	184	196	122	269	134	151	253	165	194	141	196	196	167	184·0
,,	29–Aug. 4	31	168	258	190	221	168	196	153	263	156	178	212	152	170	142	160	159	174	181·9
Aug.	5–11	32	180	170	162	227	166	164	195	245	192	198	201	215	146	130	210	202	182	185·3
,,	12–18	33	161	172	190	163	149	163	220	273	220	174	208	246	149	134	194	167	225	187·3
,,	19–25	34	115	104	157	227	141	159	148	204	212	182	178	169	161	129	145	172	190	162·5
,,	26–Sept. 1	35	118	138	105	171	99	104	101	149	164	104	113	78	91	96	75	143	185	119·5

tures for any period then become the sum of all the differences between 42° F. and the mean daily temperatures for that period. Such procedure, however, accepts all degrees of temperature as being equally effective for growth functions. As growth velocities are enhanced with advance in temperature on the chemical principle of Van't Hoff, a system of exponential indices has been adopted whereby the value of each degree, advancing from 42° F., has been enhanced by 1/18 over the one immediately below it. Due regard is also paid to extremes of temperature and of precipitation. The seasons are examined for drought periods and for extremes of heat and cold.

Daily records for rainfall and accumulated temperatures were collected for the various years from April to August inclusive.

EFFECT OF TOTAL RAINFALL AND TOTAL ACCUMULATED TEMPERATURES FOR THE GROWING SEASON.

The total rainfall and total accumulated temperatures for the growing season are shown here—reckoned from the dates of sowing to the ripening of the first variety cut.

Table IV.

Year	Range	Total accumulated temperature (day degrees)	Total rainfall (in.)	Average grain yield (bushels)
1909	Apr. 28–Aug. 18	2320	11·18	94·6
1907	„ 12–July 30	1740	10·69	90·0
1925	„ 28–Aug. 17	2253	9·45	85·0
1919	May 6– „ 28	2711	10·62	74·5
1923	Apr. 13– „ 15	2441	10·81	74·0
1908	„ 23– „ 19	2506	11·44	72·0
		Line of average yield		
1926	Apr. 17–Aug. 9	2323	11·27	66·7
1921	„ 20– „ 3	2194	9·84	64·8
1922	„ 21– „ 21	1885	9·27	64·6
1904	„ 15– „ 6	2280	11·43	63·0
1905	„ 14–July 31	2251	10·58	49·0
1906	„ 28–Aug. 15	2356	10·58	46·0

The years are here arranged in the descending order of yield. The figures for rainfall and accumulated temperatures, however, show no such tendency to range themselves in any regular order. Rather do the figures vary quite indiscriminately showing no evidence of correlation between yield and total rainfall or total accumulated temperature.

The following table is included for a few of the varieties grown in post-war years for which detailed phenological observations were made on the individual varieties. It shows that total day degree temperature requirement is not a fixed varietal characteristic but varies with each variety from year to year.

Table V. *Total day degrees of temperature from sowing to ripening.*

Variety	1919	1921	1922	1923	1925	1926
Captain	2239	2109	1822	—	—	—
Record (home grown)	2414	2351	2008	2563	2504	2549
Record (new)	2414	2202	2008	2727	2444	2449
Yielder	2508	2181	1861	—	—	—
Wide Awake	2580	2288	1951	2392	—	—
Victory (new)	2663	2246	1987	2521	2464	2509
Crown	—	2246	1879	2727	—	—
King	—	—	—	2490	2484	2548
Black Tartarian	2652	2393	1961	2542	2444	2509
Douglas Haig	—	2351	—	2363	2420	—
Black Bell 111	—	—	—	2392	2420	2413
Goldfinder	2663	2351	2071	2563	2504	2549
Golden Rain	2484	2157	1843	2392	2296	2431

It is thus obvious that neither the total rainfall nor the total accumulated temperatures for the whole growing period is correlated with yield in oats. If any correlations exist they must then be sought within shorter periods.

Distribution of Growing Seasons into Periods.

The calendar month is obviously of little significance as a time unit in its application to natural phenomena such as growth except in so far as it may chance to coincide with some critical phase of the growth cycle of the crop.

The growing seasons are next divided into arbitrary periods of 28 days starting from April 15 (the beginning of the 16th week of the year), a date which corresponds fairly with the earliest sowing dates at Aber within the years under discussion. Five such 28-day periods bring us to the end of August, and they fall thus:

1st period	16th–19th weeks inclusive		Apr. 15–May 12
2nd ,,	20th–23rd	,,	May 13–June 9
3rd ,,	24th–27th	,,	June 10–July 7
4th ,,	28th–31st	,,	July 8–Aug. 4
5th ,,	32nd–35th	,,	Aug. 4–Sept. 1

The significance of such a grouping is obvious if we single out the years 1909 and 1906—the years of highest and of lowest average yields respectively—and scrutinise them further thus:

Table VI.

	Accumulated temperatures			Rainfall		
Period	Highest yield 1909	Average for all the years	Lowest yield 1906	Highest yield 1909	Average for all the years	Lowest yield 1906
1	797 + {279 +	721 {244	630 − {178 −	3·32 − {2·16 −	4·31 {2·63	6·23 + {3·58 +
2	518 +	477	452 −	1·16 −	1·68	2·63 +
3	1133 − {520 −	1384 {615	1454 + {673 +	6·22 + {2·64 +	5·12 {2·28	4·77 − {2·11 −
4	613 −	769	781 +	3·53 +	2·84	2·66 −

In 1909, the year of highest yield, rainfall in the first two periods is below the average while accumulated temperatures are above. In the third and fourth periods, however, the position is exactly reversed, rainfall is above and accumulated temperatures are below the average respectively.

In 1906, the year of lowest yield, on the other hand, there is a complete inversion from the 1909 position. A similar scrutiny of the whole range of the other years between these two extremes of the scale of yields does not give an even gradation from the one extreme position to the other, but it does warrant further scrutiny.

Table VI gives the accumulated temperatures and rainfall for the above periods.

Table VII. *Accumulated temperatures corrected for Van't Hoff's law.*

Period	1903	1904	1905	1906	1907	1908	1909	1911	1914	1915	1916	1919	1921	1922	1923	1925	1926	Average
1st	161	234	206	178	261	244	279	299	349	258	492	244	222	123	249	166	202	243
2nd	452	526	501	452	373	524	518	586	543	429	427	669	385	465	311	438	464	477
3rd	586	607	812	673	471	716	520	596	724	694	648	599	664	459	673	598	603	615
4th	712	913	860	781	753	710	613	997	745	629	815	660	937	538	804	738	872	769
5th	574	584	614	788	555	610	664	871	788	658	700	708	547	489	624	684	782	662

Rainfall in inches.

1st	1·88	4·05	2·04	3·58	2·28	3·82	2·16	4·84	1·74	2·09	2·68	1·81	1·43	2·43	2·48	2·52	3·89	2·63
2nd	1·12	3·09	0·49	2·65	2·49	1·88	1·16	0·40	1·56	1·25	2·05	0·88	1·50	0·65	2·43	2·95	1·89	1·68
3rd	2·08	1·95	1·88	2·11	4·21	3·04	2·69	2·98	2·91	2·04	2·22	2·44	0·24	4·08	1·42	0·58	2·02	2·28
4th	5·08	2·36	3·25	2·66	1·59	3·02	3·53	2·55	1·93	2·67	0·82	2·10	6·22	2·05	2·60	2·61	2·43	2·84
5th	5·27	3·48	4·22	3·53	4·54	4·66	2·97	2·16	2·04	2·51	2·07	5·36	2·57	3·16	2·90	2·78	3·92	3·42

The relation between the three variables, yield, accumulated temperatures and rainfall was examined foı each of the 28-day periods by means of dot charts. One of these (Fig. 1), referring to a critical period defined later, is included in the text.

Accumulated temperatures in day degrees are plotted on the horizontal axis, and rainfall in inches on the vertical. The position of each year is located by a dot, and a + or − sign given to it where yield that year was respectively above or below average yield for all the years. The distribution of signs within the area indicates what relation, if any, exists between yield and the temperature or rainfall factors.

An examination of the various dot charts suggests the following correlations.

First period. With one exception in which sowing was considerably delayed, all the years with yields above the average were seasons of temperatures above the average for all the years under review. Further, there is a well-defined concentration of plus signs below the mean

rainfall line. These two facts clearly indicate the need of a dry warm period at Aber at sowing and subsequent to it if yields above the average are to be produced.

Second period. There is here no correlation.

Third period. Here we find a concentration of plus signs above the mean rainfall line.

Fourth period. A concentration of plus signs in and around the top left-hand corner offers strong evidence for the need of a cool and dry ripening period.

The first period and the last are much less arbitrary than are the second and the third, in that the first coincides with germination and establishment, while the fourth coincides with the ripening period for the run of the years. The middle periods, may, or may not, by chance coincide in some years with definite phases of the life of the crop.

There appear to be two critical periods in the life of the oat crop. The first falls somewhere in the establishment period and is favoured by higher temperature and lower rainfall than is normally experienced at this season. Cool dry weather in the earlier part of the ripening period seems concomitant with a high yield, and indicates that somewhere in late June and early July there occurs a second critical period wherein full development, leading eventually to high yields, can only be attained by rainfall higher than that normally expected.

Study of Critical Periods.

The significance of such periods with respect to crops has been clearly established. W. S. Gray (13) defines a critical period as "the interval during which the plant reaches the maximum sensibility to a given factor, and during which variations in the intensity of that factor will have the greatest effect on yield."

These periods always coincide with certain phases of growth in the crop. On narrowing down the observations on accumulated temperatures and rainfall with respect to yield in oats two such periods have been indicated, namely:

1. The 20-day period after the emergence of the oat plant in spring (the period examined in detail and found by Brouwer to be of the greatest significance in determining oat yield at Göttingen).

2. The 14-day period covering the emergence of the panicles in June and July.

(1) *Correlation of yield in oats with weather conditions for* 20 *days after emergence of the plants in Spring.*

The dot chart for this period shows the need for a warm dry seed bed to ensure high yields, while a cold wet seed bed is concomitant with grain yields below the mean. The significance of the distribution can be more fully understood by finding the correlation coefficients for yield and accumulated temperature, and for yield and precipitation for the period. From the data, these work out as follows:

Gross correlation coefficient ($r.py$) of yield of oats with precipitation at Aber for the 20 days after emergence of the plants in spring $= -0{\cdot}450 \pm 0{\cdot}134$.

Gross correlation coefficient ($r.ty$) of yield with accumulated day degrees of temperature for the same period $= +0{\cdot}447 \pm 0{\cdot}134$.

The probable error is high because the number of years under discussion (16) is small. The correlations are not of a high order. Some maintain that significance is established if r is three times the probable error, whilst others think it should be six times the probable error before definite relationship is established. When r is only twice the probable error the chance that there is a relation between the two factors is 7 to 1, when it is six times the probable error the chance of a relation comes out at 15,000 to 1.

$R\,p.y$ and $R\,t.y$, involving as they do simultaneous reactions of precipitation and temperature, and in this instance affecting yield in diametrically opposite directions, must both be regarded as gross correlations only. This is fully realised when we find that for the same period there is a third correlation ($R\,p.t$)—that between rainfall and accumulated temperatures—which has no regard to yield of a value $-0{\cdot}497 \pm 0{\cdot}126$, which is bound to mask the value of both $R\,p.y$ and $R\,t.y$, when either of these is estimated without due regard for the other. In other words, since, when the rainfall is high, temperature is generally lowered thereby, and vice versa, in reckoning the influence of rainfall without eliminating the influence of temperature we attribute to rainfall an undue effect which is in part a function of temperature involved with it and operating simultaneously. Similarly, tracing the influence of temperature, without eliminating the influence of rainfall, we attribute to temperature unduly what must be in part a function of rainfall, acting either as an obscure auxiliary to it or, as in the case here, degrading or retarding it.

Partial or net values for each of the foregoing correlation coefficients can be readily derived from the following equation:

$$r\,py\,.\,t = \frac{r\,py - r\,pt\,.\,r\,ty}{\sqrt{(1 - r\,pt^2)\,(1 - r\,ty^2)}},$$

giving in this case the net figure for the influence of rainfall after eliminating the influence of temperature.

Substituting for the ascertained values, and having due regard to signs throughout, we find that for this period

$$\text{Net } r\,py\,.\,t = -\,0{\cdot}299 \pm 0{\cdot}153,$$
$$\text{Net } r\,ty\,.\,p = +\,0{\cdot}287 \pm 0{\cdot}189.$$

As a study of the next critical period proves much more significant, high correlations could not be expected here also. There is some indication, however, that rainfall below the mean together with accumulated temperatures above the mean for the 20-day period after the emergence of the plants in spring tend to favour high yield in oats at Aber.

(2) *Correlation of yield in oats with weather conditions for the 14 days covering the emergence of the panicles.*

It is likely that in the case of any single variety this governing period of time is less than 14 days. But as the work deals with the average of all varieties grown in each year, and involves a succession of flowering dates in the whole aggregate, the flowering period is somewhat extended to cover approximately all of these.

The year 1922, which was an abnormally wet and cold year, and in which there was throughout difficulty in getting reliable phenological data, is omitted. This brings the total number of years under discussion to 15. The data for this period are treated on the same lines as those for the spring period covering the emergence of the plants, previously considered.

The dot chart (Fig. 1) for this period, is of considerable significance as the points clearly tend to a linear distribution. It indicates that high yields are concomitant with a cool flowering period of high rainfall. Weather that is during this period drier and warmer than the average coincides with low grain yields. The correlation coefficients for the period given here are of a much higher order than those for the spring period:

$$\text{Gross } r\,py = +\,0{\cdot}870 \pm 0{\cdot}042,$$
$$\text{Gross } r\,ty = -\,0{\cdot}633 \pm 0{\cdot}104,$$
$$\text{Gross } r\,pt = -\,0{\cdot}873 \pm 0{\cdot}042.$$

These are all of a high order compared with the probable error in each case. Reduced to net or partial correlations the values still remain of a high order.

Net *r py . t*—the influence of rainfall on yield of oats after eliminating the influence of temperature, for the period of 14 days covering the emergence of the panicles = + 0·841 ± 0·051.

Net *r ty . p*—the influence of temperature on yield of oats after eliminating the influence of rainfall for the same period = − 0·523 ± 0·109.

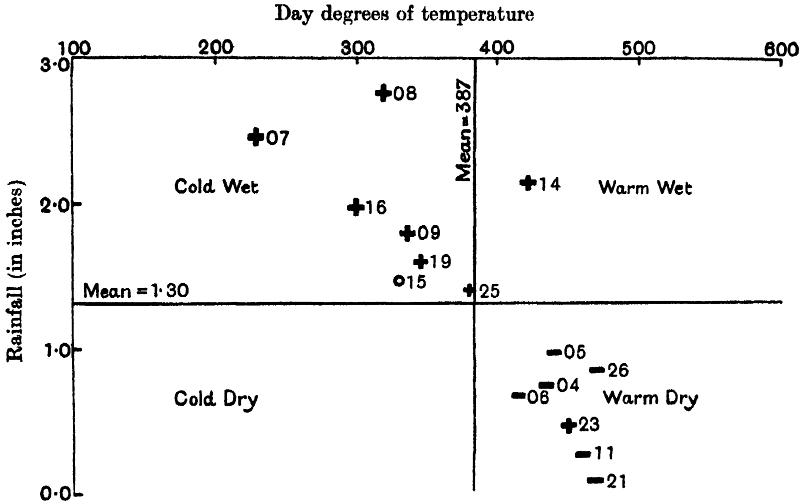


Fig. 1. Correlation of yield in oats with rainfall and temperature for 14-day period covering emergence of panicles.

Such correlations demonstrate that the period which covers the emergence of the panicles is a very critical one for oats under North Wales conditions, and ultimate yields are governed very largely by the condition prevailing at this time. This period at Aber is much more significant with respect to yield than the spring period, though both conditions operating in their respective periods tend the same way. The high correlation here found with the flowering period, a period which comes past the mid-point of the crop's occupation of the ground, is particularly significant in view of Brouwer's (*loc. cit.*) findings that the yield of the crop is already determined after the plants have occupied the ground for four weeks. He maintains that ultimate yield at Göttingen can be forecasted on the weather conditions that prevailed in this early

period. With us the highly critical period comes obviously when the panicles emerge; and any forecast of yield must at least be delayed till the weather conditions obtaining over this period be ascertained.

Significant though a scrutiny of accumulated temperatures and of rainfall for critical periods has proved, it is imperative that we should further scrutinise our data for extremes of temperatures and of rainfall, as drought periods and sequences of hot days have, elsewhere, proved harmful to the full development of cereal crops.

Scrutiny of Seasons for Drought Periods and for High Temperatures.

Grain crops require less water in the early part of growth than later, when the heads and kernels are forming and in a 10-day period of maximum transpiration the annual crops lose about a quarter of the water lost during the whole season. Transpiration of annual crops rises to a maximum a little beyond the middle of the growth period and then decreases until harvest.

In view of the above accepted physiological principles of the water requirements of annual crops a scrutiny of weather data for drought and for high temperatures is most important for our area around and over the mid-season period. Further, as oats with us occupy the ground for some 18 to 19 weeks on the average, the period for active scrutiny should be from the 8th to the 11th week and beyond, after sowing. What conditions exactly constitute a drought period are hard to define. It depends on season, sunshine, prevailing temperature, soil conditions at the time and other factors. In Russia a drought that causes plants to fail to develop and mature properly has, for convenience, been defined as a period of 10 days with a total rainfall figure below 5 mm. (0·20 in.), while in parts of the U.S.A. it has been arbitrarily defined as a period of 30 days or more in which the precipitation does not amount to 0·25 in. in any 24 hours. Critical maximum temperatures according to Brounoff have been defined elsewhere. As however drought and high maxima of temperatures, if they coincide, are likely to be more harmful than if they occurred singly, the seasons are examined collaterally for daily rainfall and maximum temperatures above 70° F. for the 8th, 9th, 10th and 11th weeks *et seq.*, after sowing, along with field notes taken from season to season and having reference to the conditions of the crops. The years are considered in two categories—years of good yields and of poor yields respectively.

Good years.

1909. There was even rain from the middle of June to the end of July. There were no days in June with maxima over 66° F. and only two days in early July touching 70° F.

1907. It rained almost daily throughout June and the first week of July. July 11–20 was dry. 71° F. was only registered once in June. Mid-July was fine but there were no hot days as the crop reached maturity.

1916. There was a drought period from July 12–31 when only 0·10 in. of rain fell, but previously rain had been quite ample. The drought was mitigated, however, by the absence of high temperatures over it.

1925. This year was dry from the farmer's viewpoint but there was no check to growth. There was even precipitation in July which in turn mitigated the high temperatures experienced in that month. Temperatures were lower as the crop ripened in August.

1914. The crop had a very good start, but it was observed that it ripened rather early. There were no drought periods—for one week only in June was no rain registered.

Bad years.

1906. The crop started well but June and July were drought months by all standards. In the first 21 days of June only 0·26 in. of rain was recorded.

1905. This was also a pronounced drought season. In May from the 11th to the 24th no rain was recorded and reckoning from May 1 to June 16 there were 36 days over which no rain fell and conditions continued dry to the end of July. June and July were also hot. Between mid-June and the end of July there were 22 days with over 70° F. maxima. As the crop ripened as early as July 31 the damaging effect of such high temperatures becomes the more evident.

1911. This year is remembered for its drought conditions. May and early June constituted a record drought period with no rain recorded for 36 days. Though the drought broke over the latter half of June it set in again for the first part of July. Besides July registered 17 days with maxima over 70° F. and from July 24–August 3 11 days had maxima from 70–82° F. This continued into August.

1904. There was intermittent rain all the summer. Average July maxima were however very high and for 11 days exceeded 70° F., and it continued so into August.

1922. This was a curiously abnormal year. The crop made a good start. Conditions were dry from the beginning of May to the third week of June, most of the rain falling in light showers of little value to the crop. From then throughout July and August there was almost constant rain with very low temperatures. In July and August there were very few days with maxima over 60° F.

1921. This was another year of marked drought. The season was good at the start and harvest conditions were good also. The intervening drought was however so severe that in 6 weeks from the beginning of June to mid-July only 0·34 in. of rain was recorded. Straw was very short and some varieties showed signs of shrivelling by the end of June. Furthermore, July maxima ran high. Of 14 days over 70° F. 12 consecutive days registered maximum temperatures of from 70–77° F.

The foregoing observations further support the general findings found elsewhere, particularly in America, that the oat plant is essentially a lover of cool conditions in its later life period. Abundance of moisture with the absence of excessive heat from flowering to ripening favour high yields. High temperatures, if unaccompanied by precipitation more especially in the later stages may prove particularly damaging to the resultant yields.

In conclusion it is of interest to review the average maximum temperatures for May, June and July for the years under discussion.

Table VIII. *Average maximum temperatures.*

	Year	May		June		July	
High yields	1909	60°		60°		63°	
	1907	58°		61°		63°	
	1916	58°	58·4°	62°	62·0°	63°	63·8°
	1925	58°		64°		65°	
	1914	58°		63°		65°	
Normal yields	1919	63°		64°		64°	
	1923	54°		60°		67°	
	1908	61°		63°		66°	
	1915	57°		61°		63°	
Low yields	1926	56°		60°		69°	
	1921	55°		61°		68°	
	1922	55°		63°		59°	
	1904	58°	57·2°	62°	62·6°	68°	68·8°
	1911	61°		61°		68°	
	1903	58°		61°		65°	
	1905	58°		66°		68°	
	1906	57°		64°		65°	

It is significant that high May maximum temperatures and relatively low July maxima are attributes of those years where yield was high, while for the years of low yield, low May maxima and high July maxima prevailed.

The average maximum temperature for July (68·8°) for the years of low yields (notwithstanding the inclusion of the abnormal year 1922 with its July maximum of 59°) stands 5° above that of the average of years of high yield (63·8°). The year 1925, which was difficult to reconcile to its relative position on other scores, fits its place in the high yield section on the score of average monthly maximum temperatures.

BRIEF SUMMARY OF OBSERVATIONS ON WEATHER AND YIELD OF OATS.

1. Seasonal variation in yield is of such magnitude as not to be masked to any appreciable degree by variations caused from year to year by changes in the personnel of the oat varieties that chanced to be grown.

2. There is no correlation between yield and total rainfall or total accumulated temperatures for the whole growing season.

3. Requirement in respect of total accumulated temperature for the growing season is not a fixed characteristic of any variety, but varies with any single variety from year to year.

4. The existence of two critical periods for oats within the growing season, the one for the 20 days after the emergence of the plants in spring, and the other for the 14 days covering the emergence of the panicles, has been shown. The correlation coefficient for rainfall and yield (*a*) and for accumulated temperatures and yield (*b*) for these periods have been determined as

(*a*) For first period:

Gross $r = -\ 0{\cdot}450 \pm 0{\cdot}134$.

Net $r = -\ 0{\cdot}299 \pm 0{\cdot}153$ for rainfall and yield.

(*a*) For second period:

Gross $r = +\ 0{\cdot}870 \pm 0{\cdot}042$.

Net $r = +\ 0{\cdot}841 \pm 0{\cdot}051$ for rainfall and yield.

(*b*) For first period:

Gross $r = +\ 0{\cdot}447 \pm 0{\cdot}134$.

Net $r = +\ 0{\cdot}287 \pm 0{\cdot}189$ for accumulated temperatures and yield.

(*b*) For second period:

Gross $r = -\ 0{\cdot}633 \pm 0{\cdot}104$.

Net $r = -\ 0{\cdot}523 \pm 0{\cdot}109$ for accumulated temperature and yield.

The significance of warm dry conditions after sowing is not as high as the significance of high rainfall and low temperatures for the emergence of the panicles, though, in this area both are concomitant with high yield.

5. The oat plant is essentially a lover of cool, humid conditions in its later life periods. High temperatures, particularly if unaccompanied

by precipitation in the later stages of ripening may prove particularly damaging to grain yields.

6. Drought periods, particularly from June onward, are likely to reduce yield, particularly if accompanied by high temperatures for the same period.

My thanks are due to my colleague Mr E. J. Roberts, M.A., M.Sc., for much valuable help in conducting the trials in the field and to Prof. R. G. White, M.Sc., for valuable help and criticism through the years (1919–1926) during which I have carried this work out at the College Farm, Aber. I am further indebted to him for access to valuable data from the farm records and for his personal observations made from season to season previous to 1911. My thanks are due also to Mr Kneller, of The Gardens, Penrhyn Castle, for ready access to all their meteorological records. Finally, to Mr Frank Hughes, laboratory assistant in my department, I tender my thanks for months of labour in sifting and assembling masses of meteorological and yield data.

REFERENCES.

(1 *a*) Engledow, F. L. and Yule, G. Udny. The Principles and Practice of Yield Trials. *The Empire Cotton Growing Review*, **111**, 1926, Nos. 2 and 3.

(1) Hooker, R. H. Correlation of the Weather and Crops. *Journal of the Royal Meteorological Society*, March 1907.

(2) Fisher, R. A. The Influence of Rainfall on the Yield of Wheat at Rothamsted. *Phil. Trans. Roy. Soc.* Series B, **213**, 89–142.

(2) The Effect of Weather on the Response of Crops to Manure. Extracts from the *Director's Report on Work at Rothamsted for the Years* 1923–24.

(3) Jones, Martin G. Effect of Weather on Oats at Aberystwyth. Welsh Plant Breeding Station. *Report of Conference at the Meteorological Office, S. Kensington, Oct.* 1 *and* 2, 1925.

(4) Brounoff, E. Some Facts Concerning the Meteorological Bureau of the Scientific Committee of the Russian Ministry of Agriculture. *Bulletin of Foreign Agricultural Intelligence*, April 1916, pp. 309–314.

(5) Bunger. Dissertation. Göttingen, 1906.

(6) Blaschke. *The Influence of the Climatic Factor*. Dissertation. Breslau, 1924.

(7) Von Seelhorst. The Water Requirements of Oat Plants under different Water and Manurial Conditions. *Journ. für Landw.* 1899.

(8) Brouwer, Walther. Relation between Yield and Climate in Agriculture. *Zeits. für Wissen. Landw.* **63**, Heft 1, January 1926, pp. 1–81.

(9) Hunter, Herbert. *The Barley Crop*. London: Benn, 1926, pp. 126–138.

(10) Hall, Sir A. D. Climate and the Wheat Crop. *Journal of the Board of Agriculture*, March 1905.

(11) Smith, J. Warren. *Agricultural Meteorology*. New York: The Macmillan Co., 1920.

(12) Kincer, J. B. Relation of Temperature to Planting and Harvesting Dates. *U.S.A. Monthly Weather Review*, April 1919.

(13) Gray, W. S. Agricultural Ecology. *Agricultural Progress*, **2**, 24–28.

(*Received November 5th*, 1927.)

INVESTIGATIONS ON YIELD IN THE CEREALS.

V. A STUDY OF FOUR WHEAT FIELDS: THE LIMITING EFFECT OF POPULATION-DENSITY ON YIELD AND AN ANALYTICAL COMPARISON OF YIELDS.

By L. R. DOUGHTY, B.Sc. (Agric.), Lond.
(Colonial Office Agricultural Scholar.)

and F. L. ENGLEDOW, M.A.
(Plant Breeding Institute, School of Agriculture, Cambridge.)

(With One Text-figure.)

CONTENTS.

§ I. Introduction.

In all field crops raised from seed, gaps and irregularities occur in the rows of plants. This characteristic is perceptible even in root crops where, by singling, special steps are taken to ensure regularity of inter-plant spacing. It is most marked, however, in corn and pulse crops. Abnormal happenings, such as temporary failure of a drill-spout, may produce long gaps or very thinly seeded stretches. Normal gaps and irregularities in plant-density, however, are localised. Their extent and nature may readily be appreciated by counting, at an early stage, the number of plants in successive short lengths of the rows (drill rows). That within fairly wide limits individual plant development is enhanced by liberal spacing is well known. In principle, it may be held that gaps and thin places are "compensated," in the final yield of grain, by the vigour of individual plant growth and notably, in the cereals, by profuse tillering.

In a series of experiments (*vide* (1), (2) and (3)) the nature and extent of point-to-point fluctuations in plant density have been measured in typical field crops. The causes of this fluctuation and its relation to yield per acre have also been examined. The method employed may be described as a "census of an acre by sampling," and full details of this are given in (1) and (4). Briefly, it involves the selection of an acre in a standing crop, and the drawing from this of one hundred samples, suitably dispersed. A sample is a one-foot length of drill row, the plant population in every sample length being counted and examined for tillering and other features. The statistical reliability of the method, fully discussed in (1) and (4), must, of course, be put to test in the case of every count.

It has been inferred from these earlier experiments that, in aggregate, the characteristic small gaps and "thin places" involve a substantial loss of potential yield. In so saying it is necessary to insist upon the fact that the fluctuations in plant density concerned are sharply localised. They represent the irregularities from point to point along a row of plants. In a typical case the numbers of plants per foot in succession along a row were found to be 20, 11, 12, 14, 5, 8, 17. Only by assessing this fluctuation in a field crop and by determining the rate of yield for different density-aggregates, is it possible to relate yield per acre to fluctuation in density of plant.

Before accepting the inference that spatial fluctuation effectively limits yield in typical field crops, all possible alternative explanations must be explored. Thus, for instance, "compensation by increased tillering" must be fully examined. Again, it may be argued, that the correlation between number of plants and yield in short lengths of row is spurious. It may be that both values are low at one point because unfavourable soil conditions there limit both the number of plants surviving and the development of the survivors. These and other alternatives to the inference outlined above were dealt with in the earlier experiments. But the point at issue is of considerable economic importance and extended re-investigation has therefore appeared necessary. This has taken the form of a census-analysis from seeding to harvest on four fields of wheat in 1926–7. These fields were chosen, well in advance of sowing time, to afford a good range of soil condition, level of fertility, and standard of husbandry.

Six purposes were in view:

1. To make a thorough ascertainment of the nature and degree of fluctuation in plant density in typical field crops.
2. To seek the chief causes of this fluctuation.
3. To determine the influence of this fluctuation on yield per acre.

4. To ascertain whether, in the aggregated short lengths of row having low density of plant-population, the yield is solely or mainly limited by paucity of plants.

5. To gain more knowledge of developmental history in typical field crops.

6. To afford an analytical basis of comparison between good, medium and bad fields of wheat.

§ II. THE FOUR FIELDS AND THE DISTRIBUTION OF SAMPLES.

The four fields, all in Cambridgeshire, will be referred to as Fields *D*, *G*, *L*, and *P*.

Field D. Soil a clay, intermixed with gravel and on a heavy clay subsoil; in good heart and well cultivated; sowing on Nov. 12 on an excellent wheat seed-bed, firm below and suitably fine on top; an 8-coulter cup drill in good working order was used; Yeoman wheat sown at an intended rate of 2½ bushels per acre; an excellent sample of seed; the seed steeped in formalin and held over for four days on account of bad weather; as later explained, actual germination in the soil was low owing, it is believed, to delay in sowing after formalin-steeping; a dressing of 1 cwt. per acre of sulphate of ammonia on March 4; the crop grew well throughout the season and was not seriously affected by pests, disease, or lodging; harvest under good conditions on Aug. 6.

Field G. Soil a stiff clay and not well drained; in fair heart and well cultivated; sowing on Nov. 1 on a seed-bed which for the land and season was good; tilth not rough but somewhat sticky after recent frosts; a 9-coulter cup drill in fair working order; Cambridge Browick wheat sown at an intended rate of 2½ bushels per acre; a very good sample of seed; a dressing of 1 cwt. per acre of sulphate of ammonia on March 16; growth appeared to be somewhat inhibited by wetness at the end of winter but was otherwise good; no serious injury from pests or diseases; harvest under good conditions with some difficulty from partial lodging on Aug. 5.

Field L. Soil a medium-heavy clay, well drained, and in fair heart; badly farmed for some years prior to 1926 and since then intensively farmed to restore fertility and condition; sowing on Oct. 27 on a seed-bed which, though sticky on top was firm below and in general extremely good for the land and season; an 11-coulter cup drill, new and in perfect order; Yeoman wheat sown at an intended rate of 2½ bushels per acre; an excellent sample of seed; a dressing of 1 cwt. per acre of sulphate of ammonia on March 4; good growth all through the season; no serious damage from pests, disease, or lodging; harvest in good order on Aug. 6.

Field P. Selected as an inherently difficult field and in anticipation of a somewhat low level of husbandry; soil a heavy clay; badly drained and frequently water-logged in winter; in poor heart and cultivated at minimum expenditure; sowing on Oct. 21 after rough preparation but in a period of favourable weather; a 10-coulter cup drill much worn in all the working parts; Yeoman wheat sown at an intended seed-rate of 2½ bushels per acre; a poor seed sample with 18 *per cent.* grown corns; no spring top-dressing; a very thin plant from the start; despite liberal spacing (owing to initial thinness) growth was poor throughout the season and weeds abundant; a thin stunted crop at harvest; no serious damage from pests, disease, or lodging; harvest on Aug. 15.

On every field a rectangular acre was selected, this being as fairly representative as could be practically determined, of the whole field. On this acre one hundred sample points were marked. These were so distributed as to cover the acre evenly and to represent equally the work of all the coulters of the drill. At each sampling point a one-foot length of row was marked by two pegs, three inches in length, protruding an inch from the surface, inserted at sowing time and allowed to remain till harvest. The position of a sampling-point was determined laterally by counting number of drill rows and, along the row, by measurement. To avoid bias the first peg marking the foot, was inserted precisely at the point reached by measurement. On fields *D* and *G* every sample was duplicated. That is to say, at every sample point, two adjoining one-foot lengths were observed. The two feet of such a pair were designated α and β. Duplication was for the purpose of analysis as later employed. Counts were made of the seed actually sown, then periodically of the growing plants, and finally, at harvest, samples were gathered on their roots. Subsequently the harvest samples were counted, the tillering determined, and the grain per one-foot sample threshed and weighed. Certain additional counts proved necessary as explained in later passages.

§ III. Fluctuation in Plant-population Density in Field Crops.

For convenience, the data and results arising from counts of the seed-sowing have been separately published (4). With them have been included, in confirmation, the early plant-count results. Two special additional forms of count had to be made. On two of the fields there was a special seed count on long successions of foot-lengths, the data from which are fully illustrated in (4). Further, in three of the fields, a per-inch count of plants was made by a specially devised method as soon as effective

germination was complete (*vide* (4)). It was emphatically shown that on all four fields seed-distribution by the drill was highly irregular from inch to inch and from foot to foot along the row. The irregularity was random in the sense that the deposit of seeds on any short length bore no significant relation to that on the previous or next-following length. Plant-counts, immediately after germination, checked and substantiated this conclusion.

In completion of evidence it is necessary to consider here the population-data at harvest. For the four fields:

	D		*G*			
	α series	*β* series	*α* series	*β* series	*L*	*P*
Mean plants per foot...	12·8	12·6	13·9	12·7	17·5	8·8
Standard deviation of plants per foot	5·8	5·1	5·7	5·7	6·4	4·8

Table I. *Frequency distribution of number of plants per foot at harvest on fields* D, G, L, *and* P.

	No. of plants per foot												
Field	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
D (*α* series)	1	3	1	1	—	3	2	7	7	8	6	5	4
D (*β* series)	—	—	1	2	3	2	1	4	8	8	4	16	7
G (*α* series)	—	2	1	1	1	3	4	1	1	4	7	5	11
G (*β* series)	1	1	1	1	—	3	3	9	8	8	4	7	6
L	—	—	—	—	1	—	—	2	4	—	7	6	4
P	2	2	2	6	7	8	8	6	10	11	5	11	4

	No. of plants per foot												
Field	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*
D (*α* series)	7	6	7	4	5	4	5	5	2	—	3	2	1
D (*β* series)	7	3	5	4	5	5	5	5	2	1	1	—	—
G (*α* series)	3	12	8	7	5	4	5	2	4	1	3	1	2
G (*β* series)	6	6	4	8	4	2	7	3	2	1	—	1	2
L	6	6	9	3	6	5	3	6	6	5	3	3	3
P	4	2	1	3	3	1	1	2	—	—	—	—	1

	No. of plants per foot												
Field	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*	*35*	*36*	*37*	*38*
D (*α* series)	1	—	—	—	—	—	—	—	—	—	—	—	—
D (*β* series)	—	—	—	—	1	—	—	—	—	—	—	—	—
G (*α* series)	1	—	—	—	—	—	—	1	—	—	—	—	—
G (*β* series)	1	—	—	—	1	—	—	—	—	—	—	—	—
L	1	3	4	1	1	1	—	—	—	—	—	—	1
P	—	—	—	—	—	—	—	—	—	—	—	—	—

In Table I is given the frequency-distribution of number of plants per foot for the separate fields. This table discloses for all four fields a wide fluctuation in number of plants per foot at harvest. The facts may be more readily grasped by condensing the distributions into five quintiles, or equal one-fifth-frequency portions. These quintiles, called

Q 1 to Q 5, are specified by the values in the top two rows of Table II, D, G, L, and P[1]. Even on the most regularly populated field, viz. field L, equal one-fifth aggregates have, as mean numbers of plants per foot, the values 9·3, 13·5, 16·7, 20·9, and 27·0.

Table II. D. *Attributes of the quintiles* (Q 1 *to* Q 5) *of the frequency-distribution of number of plants per foot on field* D *at harvest.*

	Q 1	Q 2	Q 3	Q 4	Q 5
Limits of range (number of plants per ft.)	0·0–7·3	7·4–10·1	10·2–13·8	13·9–17·7	17·8–26·0
Mean number of plants per ft.	5·0	9·2	12·6	16·1	21·2
Mean number of ears per plant	1·92	1·82	1·83	1·84	1·64
Mean yield per ear (grammes)	1·29	1·30	1·23	1·21	1·22
Mean yield per plant (grammes) ...	2·47	2·37	2·25	2·23	2·00
Mean yield per foot (grammes)	12·4	21·7	28·5	35·9	42·3
Equivalent yield per acre (bushels) ...	28	50	65	82	96

Table II. G. *Attributes of the quintiles* (Q 1 *to* Q 5) *of the frequency-distribution of number of plants per foot on field* G *at harvest.*

	Q 1	Q 2	Q 3	Q 4	Q 5
Limits of range (number of plants per ft.)	1·0–9·3	9·4–11·9	12·0–14·5	14·6–18·0	18·1–33·0
Mean number of plants per ft.	6·1	11·3	13·9	16·5	22·2
Mean number of ears per plant	1·28	1·18	1·12	1·12	1·03
Mean yield per ear (grammes)	1·52	1·54	1·45	1·41	1·14
Mean yield per plant (grammes) ...	1·95	1·82	1·62	1·57	1·18
Mean yield per foot (grammes)	11·8	20·5	22·6	25·9	26·1
Equivalent yield per acre (bushels) ...	27	47	52	59	60

Table II. L. *Attributes of the quintiles* (Q 1 *to* Q 5) *of the frequency-distribution of number of plants per foot on field* L *at harvest.*

	Q 1	Q 2	Q 3	Q 4	Q 5
Limits of range (number of plants per ft.)	4·0–11·0	11·1–14·5	14·6–18·3	18·4–22·3	22·4–38·0
Mean number of plants per ft.	9·3	13·5	16·7	20·9	27·0
Mean number of ears per plant	1·47	1·34	1·22	1·18	1·11
Mean yield per ear (grammes)	1·26	1·23	1·20	1·14	1·06
Mean yield per plant (grammes) ...	1·85	1·64	1·46	1·35	1·18
Mean yield per foot (grammes)	17·2	22·2	24·5	28·1	31·9
Equivalent yield per acre (bushels) ...	39	51	56	64	73

Table II. P. *Attributes of the quintiles* (Q 1 *to* Q 5) *of the frequency-distribution of number of plants per foot on field* P *at harvest.*

	Q 1	Q 2	Q 3	Q 4	Q 5
Limits of range (number of plants per ft.)	0·0–4·1	4·2–6·9	7·0–8·8	8·9–11·5	11·6–25·0
Mean number of plants per ft.	2·9	5·9	8·2	10·9	16·0
Mean number of ears per plant	1·47	1·31	1·30	1·20	1·09
Mean yield per ear (grammes)	1·14	1·13	1·10	0·91	0·95
Mean yield per plant (grammes) ...	1·67	1·49	1·42	1·08	1·04
Mean yield per foot (grammes)	4·8	8·8	11·7	11·8	16·6
Equivalent yield per acre (bushels) ...	11	20	26·5	27	38

[1] For D and G, only the α series is given. The β series, while necessarily slightly different in absolute values, shows very close agreement in general form.

The data here given for harvest population, together with those of the earlier paper(4) for seeding and young plants, leave no doubt that in typical fields of wheat sharp fluctuations in per-foot density of population are characteristic. Degree of fluctuation varies from field to field but wide fluctuation is to be found in every field. In the past, seed-rate (*i.e.* average number of seeds per unit length of row) has been the subject of frequent debate and experimentation. The extent and influence of irregularity of seed-deposition and plant-population have been overlooked.

§ IV. THE CAUSES OF FLUCTUATION IN PLANT-POPULATION DENSITY.

Irregularity in number of seeds sown and of plants surviving to harvest, as among small unit lengths of row, may be traceable to many causes. These may be broadly classified:

1. Irregular per unit length deposition of seed by the drill resulting from:

(*a*) Mechanical imperfections inherent in the drill.

(*b*) Large foreign objects, *e.g.* chobs, in the seed, which interfere with seed-flow in the drill.

(*c*) Bad condition of seed, *e.g.* from faulty copper sulphate dressing inducing irregular seed flow.

(*d*) Irregularities in tilth, and soil variations, disturbing drill action.

2. Low effective germination of seed due to inherently low germination capacity (effective germination implies emergence of viable plumules from the soil and thus, in some seed samples, may differ from laboratory germination).

3. Reduction of effective germination brought about mechanically as by deep burying of seeds or seeds being covered by large clods.

4. Destruction of plants or seeds by insects, fungi, birds, etc.

5. Destruction of plants by frost, water-logging, etc.

Causes grouped under 2, 3, 4, and 5 differ from those under 1 in that neither by eye-observation nor by counting can their action, as a rule, be at all accurately assessed. It will therefore be convenient to discuss them first, leaving causes grouped under 1 for separate consideration.

Low effective germination undoubtedly contributes to the kind of fluctuation under consideration. It is difficult to explore this question theoretically as may be perceived from an example. Thus on field *D* effective germination was low because of injury from the formalin dressing, while on field *P* the seed contained nearly 20 per cent. of "grown" corns. In the latter case low germination capacity might be expected to induce fluctuation in number of seedling plants per foot, of an

order represented by $(p+q)^x$. Here $p = \frac{1}{8}$, $q = \frac{7}{8}$ and x = number of seeds sown per foot. But, as explained below, x fluctuates markedly. Thus, while the possibility of fluctuation owing to low germination is patent, its degree appears not readily determinable. It is important to notice, however, that on fields G and L the seed sample was of very high germination capacity. In spite of this the per-foot distribution of seedling plants on both these fields showed strong fluctuation. Actually, for the seedling count, the coefficients of variation ($V = 100\,\sigma/M$) were:

Field	D	G	L	P
V (for number of seedling plants per foot)	48·6	43·8	31·4	58·6

There is a significant difference between fields L and P. This, no doubt, is partly due to low germination capacity of the seed sown on P. Another contributory cause must have been the much worn drill and rougher tilth in contrast with the excellence of drill and tilth in the case of L (*vide* § II, *supra*). Apart from this difference, however, all the fields may be said to display a fluctuation of high order. Thus it is concluded that while low germination may contribute to per-foot fluctuation it is of secondary importance in normal field crops.

Reduction of effective germination by deep burying of seeds or seeds being covered by large clods was not an important factor in the four fields. Sometimes, in really rough sowings, especially in those made immediately behind the steam plough, this reduction may be important. Even then its action is not sharply localised. It is not, experience suggests, usually confined to isolated and randomly dispersed lengths of the order of one foot.

Plant losses from insects, fungi, birds and other agents of destruction were very few on the four fields. Where such losses are heavy they are not very sharply localised and randomly dispersed. Wire-worm may severely damage a field but lengths of several feet of rows are usually affected and it is usual for one end or corner or other major portion to be much more severely attacked than the rest.

Young plants may be killed by frost, water-logging and other analogous agencies. If such losses were largely responsible for fluctuations in per-foot density then the fluctuation at harvest should be much greater than in the seedling stage. This has not been the case in any census count so far made. For the fields here discussed the coefficients of variation of number of plants per foot were:

Field	Seedling population	Harvest population
D	48·6	45·3
G	43·8	41·0
L	31·4	36·6
P	58·6	54·5

The foregoing considerations suggest that the prime cause of irregularity of plant density must lie in the operation of sowing, *i.e.* in the causes 1 (*a*)–(*d*) above. For (*b*) and (*c*) estimation is impossible. That they are contributory causes is familiar to all who have used a seed drill. There remain the causes grouped as 1 (*a*) and 1 (*d*) (above). These have been very fully discussed in an earlier publication (*vide* (4), §§ VI and VII). The evidence clearly suggested that while soil variations and tilth irregularities induced fluctuations in seeding by disturbing the working of the drill, it was in the inherent mechanical action of the drill that the chief cause of fluctuation lay. By a mechanical analysis of drill action it was shown that the outstanding defect was marked inconstancy in the number of seeds deposited into the hopper at different times by any and every cup on the drill-barrel.

Thus, while a number of contributory causes can be named, the prime cause of fluctuation in plant-population density is irregularity in seed-deposition by the drill.

§ V. THE INFLUENCE OF FLUCTUATION IN PLANT-POPULATION DENSITY UPON YIELD PER ACRE.

That density of plant-population fluctuates sharply from point to point along the row has been shown in § III (*supra*). This fluctuation must be regarded as a normal characteristic of field crops of corn. Its degree varies from field to field but appears never to be less than is represented by a coefficient of variation of some 35–45 per cent. The extent to which this characteristic fluctuation reduces the actual yield per acre below the maximum potential yield appropriate to the soil and other circumstances must now be considered.

The most direct procedure is to determine the rate of yield associated with every gradation of population density. It will be seen from Table I that the range of fluctuation is wide and that the extremes of density gradation (numbers of plants per foot) have very low frequencies. Density gradations must therefore be grouped. Partition of the frequency distribution into five equal-frequency portions or quintiles is a convenient grouping. In Table II, *D*, *G*, *L* and *P* the characteristics of the quintiles (designated *Q* 1 to *Q* 5) are given for the respective fields.

On field *D* (Table II, *D*) an aggregate (*Q* 1) of one-fifth of the acre consisted of foot-lengths having from 0 to about 7 plants each, the mean number of plants per foot for this aggregate being 5·0. There was an average of 1·92 ears per plant for this aggregate, the average yields of grain in grammes being 1·29 per ear, 2·47 per plant, and 12·4 per foot.

The second aggregate or quintile, Q 2, included foot-lengths with about 7 to 10 plants each, the mean for the aggregate being 9·2 plants per foot. At this somewhat closer spacing the average number of ears per plant was 1·82, *i.e.* slightly lower than for Q 1. Yield per ear was effectively the same as for Q 1 and yield per plant slightly less. But with a greater average number of plants per foot the rate of yield per foot was far higher than for Q 1 (21·7 grammes as compared with 12·4 grammes). The sequence of values described for Q 1 and Q 2 may similarly be followed through Q 3, 4, and 5. It is important to notice that every sequence is unbroken by exceptions save in the case of average yield per ear. For this the exceptions are, however, very slight.

The effects above considered are integrated in the bottom row of Table II, D, which shows the equivalent per acre yields for the populations which constitute the separate population-density quintiles. For the whole acre the yield is about 64 bushels. For the quintile aggregates it sinks as low as 28 bushels for Q 1 and is no less than 96 bushels for Q 5. Let it be assumed, for the present, that differences in plant-population density are the sole cause of inter-quintile differences in rate of yield. Then it must be inferred that 96 bushels per acre represents the potential yield of the land. Consequently the actual yield represents a reduction of $96 - 64 = 32$ bushels on the potential maximum. Strictly analogous results are disclosed by an examination of the data for the other fields (Table II, G, L, and P). Inter-field comparison is reserved for §§ VI–VIII (*infra*).

In interpretation of these somewhat striking differences the essential features are the relative constancy of yield per ear at different population densities and the slow decline in ear-production with decrease of inter-plant spacing. It appears, in short, that under field conditions and within the spatial range represented by field crop, paucity of plants is not effectively counteracted or "compensated" by prolificacy of tillering and enhanced size of ear.

The relation between population density and yield may be studied as a correlation. For the four fields, the coefficients of correlation between number of plants per foot and yield of grain per foot were:

Field	D (α series)	D (β series)	G (α series)	G (β series)	L	P
Coefficient of Correlation	+ 0·80	+ 0·75	+ 0·58	+ 0·65	+ 0·66	+ 0·67

Every value is based on one hundred samples so that a strong, significant, positive correlation must be regarded as characteristic of all the fields. What this correlation signifies may be gauged from the equations of the

lines of regression. If Y = yield (grammes) of grain per foot and X = number of plants per foot these equations are:

For field D (α series) $Y = 1{\cdot}85\,X + 4{\cdot}52$.
For field D (β series) $Y = 1{\cdot}74\,X + 5{\cdot}73$.
For field G (α series) $Y = 0{\cdot}86\,X + 9{\cdot}35$.
For field G (β series) $Y = 0{\cdot}96\,X + 8{\cdot}26$.
For field L $Y = 0{\cdot}80\,X + 10{\cdot}79$.
For field P $Y = 0{\cdot}78\,X + 3{\cdot}86$.

These equations allow Y (yield per foot) to be calculated from X (number of plants per foot). As an example the calculated yields per foot corresponding to the mean numbers of plants per foot for separate quintiles may be noted. Thus for field D (α series):

	$Q\,1$	$Q\,2$	$Q\,3$	$Q\,4$	$Q\,5$
Calculated yields per foot (grammes)	13·8	21·5	27·8	34·3	43·7
Actual mean yields per foot (grammes)	12·4	21·7	28·5	35·9	42·3

Close agreement between calculated and actual quintile yields is found, also, for the other fields.

For an increase of one plant per foot over the whole acre, the increase in per-foot yield (grammes) is given by the coefficient of X in the above regression equations. Converting into bushels per acre these increases in per acre yield corresponding to unit increase in number of plants per foot are:

Field	D (α series)	D (β series)	G (β series)	G (β series)	L	P
Increase in yield (bushels) corresponding to unit increase in number of plants per foot	4·22	3·97	1·96	2·19	1·82	1·78

These numbers attest that in the circumstance of typical field crops of wheat, population density, in the sense here used, is an important determiner of yield.

As a final consideration the whole question of yield-determination may be reopened from an independent point of view. It may be argued, at large, that fluctuation in yield from short lengths of row is primarily induced by corresponding fluctuations in soil conditions. This would involve, on reasoning fully given in an earlier paper (*vide* (4), § V) and in § IV (*supra*), a correlation between yields from adjoining short lengths of row. Now in fields D and G samples were duplicated. That is, at every sampling point, two adjoining one-foot lengths, denoted by α and β, were taken. The yield correlation, $r_{\alpha.\beta}$, proved to be:

$$\text{For field } D,\ r_{\alpha.\beta} = +\,0{\cdot}11;\ \text{for field } G,\ r_{\alpha.\beta} = +\,0{\cdot}275.$$

These values, each based on one hundred pairs, are non-significant. Thus

the possibility that soil conditions, rather than population density, determine yield from short lengths of row must be dismissed. It may be noted that the $r_{\alpha.\beta}$ correlations for yield afford an experimental check on the evidence and reasoning of preceding passages. Thus, in an earlier paper (*vide* (4), § VI) it was proved that no correlation subsists between numbers of seeds sown on adjoining foot-lengths of row. Among seedling plants a corresponding absence of correlation was recorded. From the later counts it appears that this state of affairs persists throughout the life of the crop. On fields *D* and *G* at harvest the value of $r_{\alpha.\beta}$ in respect of numbers of plants in adjoining one-foot lengths was:

$$\text{For field } D,\ r_{\alpha.\beta} = -\ 0{\cdot}038; \text{ for field } G,\ r_{\alpha.\beta} = -\ 0{\cdot}066.$$

Characteristically then:

(*a*) There is no correlation between numbers of plants on adjoining foot-lengths of row (as above and also in (1) and (2)).

(*b*) There is a high correlation between number of plants per foot at harvest and yield per foot.

From (*a*) and (*b*) it follows that:

(*c*) There should be no correlation between yields from adjoining foot-lengths of row.

Inference (*c*) harmonises with the values given above for $r_{\alpha.\beta}$ in respect of yields from adjoining foot-lengths. Thus experimental confirmation is afforded for the chain of reasoning by which, in preceding passages, yield per foot-length is shown to be directly and causally connected with number of plants per foot-length.

Another line of consideration may be followed. If, over the acre, fluctuations in yield per foot are markedly related to fluctuations in population density, the fact should be demonstrable by measurements of dispersions. Thus, for an aggregate of foot-lengths, all having the same number of plants per foot, the standard deviation of yield per foot should be less than for the combined samples from the whole acre. Irregularities of spacing naturally occur within the foot-length itself. Apart from the influence of these, however, the standard deviation of yields from foot-lengths having the same number of plants, may be taken to represent fluctuation in yield attributable to soil. Extreme gradations of plant density cannot be considered for their frequencies of occurrence are very low. On fields *D*, *G*, and *L* the foot-lengths were aggregated (excluding extremes) as follows: 7–8, 9–10, 11–12, and 13–14 plants per foot. For field *P* the grouping was: 5–6, 7–8, 9–10, and 11–12 plants per foot. On all fields the standard deviation of yield per foot was much

lower in every such aggregate than for the whole acre (100 samples). Field *G* may be used to illustrate this:

Spatial aggregate	σ	V
All samples (α series)	8·54	40·0
All samples (β series)	8·42	41·3
7– 8 plants per foot	4·60	31·1
9–10 plants per foot	5·88	31·4
11–12 plants per foot	6·26	30·7
13–14 plants per foot	5·70	25·0

Here σ = standard deviation of yield per foot and $V = 100\,\sigma/M$ where M = mean yield per foot.

Thus quite apart from fluctuation in yield induced by soil variation there is a very strong influence exerted by density of population.

The results derived from four very different fields of wheat in 1926–7 harmonise fully in principle with those from barley fields in 1924–5 and 1925–6(2), as also from wheat fields in 1922–3 and 1923–4(1). Also root crops(3) afford further affirmations of the general principle. The degree of relationship between yield per acre and population density (in the sense here employed) must necessarily vary from field to field and season to season. But that population density is an important limitation to yield in typical field crops of this country appears beyond doubt.

§ VI. Comparative Plant Development in the Four Fields.

In every parish, the wheat fields show, *inter se*, marked differences in yield. These, while unusually emphatic in some seasons, are a feature of every season. It is customary to ascribe them to differences in soil, previous cropping, and the other, very numerous, known external factors of yield. Analysis, with so many factors involved, presents problems of the greatest complexity. For that reason certain controllable circumstances are apt to be forgotten in a not-unnatural feeling that yield is essentially an inscrutable expression of "soil and season." Nevertheless, in foregoing passages, a clear relation has been traced between yield per acre and the partially controllable factor, population density. The data accumulated in studying this factor offer a basis for inter-field comparison. In essaying this comparison attention will be drawn to certain controllable circumstances. At the same time an endeavour will be made to assess, relatively, innate differences of soil and fertility.

Yield is an ultimate expression or integration of plant development. For this reason a developmental basis is given to the inter-field comparison. A number of counts was made of population density and tillering. In some cases the desired count had to be omitted because it would have

involved injury by puddling the soil and one important count was prevented by a spring harrowing (field *L*). The chief agricultural circumstances of the fields have already been described in § II (*supra*). Seed sowing is not brought directly under consideration as it has been dealt with at length in an earlier paper (4). On fields *D* and *G* duplicate samples, *α* and *β*, were observed at every count. Agreement between the two series is, however, so close that only the *α* series is employed here.

Table III. *A résumé of plant development and yield on four fields.*

	Field *D*	Field *G*	Field *L*	Field *P*
Variety of wheat	Yeoman	Cambridge Browick	Yeoman	Yeoman
Date of sowing	12/11	1/11	27/10	21/10
First count:				
Date	21/12	30/11	29/11	21/12
Average number of plants per foot	10·7	14·3	19·7	9·6
Second count:				
Date	19/1	25/1	Not counted	Not counted
Average number of plants per foot	11·4	15·4		
Third count:				
Date	28/1	Not counted	4/2	1/2
Average number of plants per foot	12·6		18·7	10·4
Sulphate of ammonia, top dressing at 1 cwt. per acre: Date	4/3	16/3	4/3	None
Fourth count:				
Date	8/3	9/3	Not counted	11/3
Average number of plants per foot	9·8	13·7		9·0
Average number of side tillers per plant	1·2	1·5		0·6
Correlation: plants per foot and side tillers per plant	+0·26	−0·06		+0·15
Fifth count:				
Date	25/4	26/4	23/4	28/4
Average number of plants per foot	10·8	13·9	17·3	10·2
Average number of side tillers per plant	5·7	2·7	3·7	1·4
Correlation: plants per foot and side tillers per plant	−0·48	−0·61	−0·59	−0·41
Sixth count (harvest):				
Date	6/8	5/8	6/8	15/8
Average number of plants per foot	12·8	13·9	17·5	8·8
Average number of ears per plant	1·73	1·16	1·28	1·32
Correlation: plants per foot and ears per plant	−0·24	−0·34	−0·51	−0·42
Percentage of April tillers (fifth count) which formed ears	25·8	31·4	27·2	55·0
Rate of yield per acre (bushels)	64·5	48·6	56·5	24·4
Average yield per foot of row (grammes)	28·3	21·4	24·8	10·7
Average yield per plant (grammes)	2·20	1·53	1·42	1·22
Average yield per ear (grammes)	1·24	1·37	1·16	1·01
Weight of 1000 corns (grammes)	39·5	47·9	42·9	40·3
Average number of grains per ear	31·4	28·6	27·1	25·1
Correlation: plants per foot and yield per foot	+0·80	+0·58	+0·66	+0·67

Table III is a résumé of data concerning plant development and yield.

In the case of every field the intended seed-rate was $2\frac{1}{2}$ bushels per acre, corresponding, for rows at 8 in. apart, to about 18–20 seeds per foot. Seed counts made immediately behind the drill are fully recorded in an earlier paper (4). As there explained it is very difficult to count seeds accurately, especially on a rough tilth. Consequently discrepancies between the seed count and the first count of plants are inevitable. Their extent cannot well be checked because it is masked by deficient germination (*vide* (4), § III). With necessary reservations the estimated numbers of seeds sown per foot were for field $D = 17{\cdot}7$, $G = 16{\cdot}5$, $L = 18{\cdot}0$, $P = 11{\cdot}9$. It is reasonable to infer that on three of the fields the intended amount of seed was sown. On field P, however, only about 65 per cent. was sown. This deficient seeding was reasonably attributable to the very worn and neglected condition of the drill.

Effective germination calls for attention. On field D, where some 17 seeds per foot were sown, only about 12 or 13 plants appeared and survived. Delay in drilling of formalin-dressed seed was almost certainly the cause of loss. Overnight dressing of seed is commonly practised and sudden rain frequently delays drilling. There is ample evidence that germination-reduction through use of formalin is of frequent occurrence. It is even possible that in aggregate formalin treatment losses counterbalance the probable losses from bunt which the treatment prevents. A bad sample of seed was sown on field P: it contained 18 *per cent.* of sprouted corns. The consequent low germination aggravated the already bad situation created by very imperfect drilling. Not every sample of seed wheat is even reasonably good and it appears proper to urge that greater care with seed and sowing in general would be of definite assistance to wheat-growing.

Crop-life commenced with the average populations shown in the first count (Table III). Up to February there were few changes. Some plants died but late germinations tended to counterbalance this loss. In the field, effective germination may be very protracted. Even on carefully dibbed plots a few newly emerged plumules may be seen (wheat) as late as fourteen weeks after sowing.

In February growth was manifestly, to the eye, very slow on all the fields. Signs of "winter sickness" and "yellowing" however were not marked; the condition of all the fields was normal for the time of year. The fourth count gives an index to development at the beginning of March. That tillering is significantly low on field P may be presumed to

reflect extreme wetness and low fertility. It will be observed that no significant correlation was found, at the fourth count, between average population density and tillering (average number of side tillers per plant, *i.e.* tillers additional to the main axis). Up to the time of this count (first week in March), therefore, individual plant growth suffered no limitation from spacing.

Sulphate of ammonia at 1 cwt. per acre was applied, early in March, to fields *D*, *G* and *L* but not to field *P*. The application was, from the appearance of the fields, conformable with and required by good farming practice. It appeared most necessary in field *P*. A fifth count of plants and tillers was made towards the end of April. By this time the fertiliser had wrought a great change in the appearance of fields *D*, *G* and *L*. Field *P* looked unpromising. The plants, though so liberally spaced were obviously not well tillered and the foliage while not "yellowed" was definitely of a sickly colour. There were certain facts of interest at this stage in the top-dressed fields *D*, *G* and *L*. On field *D* growth was very vigorous. The older tillers of the plants were well developed and there was a profusion of later tillers. Many of these were very small and not a few were "blind." Blind tillers are very small, late shoots which never emerge more than a single leaf, the growing point, for some reason failing to develop. Field *L*, also carrying Yeoman wheat, was of very healthy colour but later in development than field *D*. The chief stems of the plants were smaller and tillering was clearly less profuse. The lower density of population on field *D* probably explained part of the difference. From the lesser size of the more forward stems on field *L*, however, it may be surmised that inherent differences in soil, drainage, and fertility were also reflected.

The actual data for population density and tillering towards the end of April are shown in Table III (fifth count). A larger number of plants is recorded for fields *D* and *P* than at the fourth count. For the fifth count samples one yard distant from the marked samples were dug up and counted for tillers and plants. Thus the data of the fifth count are more reliable than those of the previous occasion when exact separation of plants without lifting was beginning to be difficult. The profuse tillering of field *D*, a reflection of good drainage and high farming, is a noteworthy feature of this count. Another is the very feeble tillering of field *P* which must be attributed to bad conditions of drainage, low farming and failure to apply a top dressing. On all fields a strongly negative correlation is shown between tillering and population density. It is thus evident that spatial influence began to assert itself between the

fourth and fifth counts (roughly, say, at about the end of March). When, as in the passages which follow, attention is given to the proportion of April tillers which form ears, some interesting questions arise. Tillering is definitely known (from data not yet published) to continue well into May. In all corn crops more than half the total tillers which form die out, mostly at a fairly early stage. That these ephemeral tillers do nothing to assist the larger tillers on which ears finally form appears probable, though experimental proof is wanting. It is, then, only from early-formed tillers that the harvest is reaped. Comparing number of ears per plant (sixth count) with number of early tillers (fourth count) it seems safe to assume that, as an average effect, tillers which arise after at any rate the end of March do not form ears but die. There is, in effect, a "critical time" for tiller formation. It is necessarily variable with circumstances of soil, season, population density and treatment of the crop. But on its approximate determination must depend the intelligent use of nitrogenous top dressings and also the correlation of final yield with developmental history. (Note: In the fourth and fifth count number of tillers refers to side tillers additional to the main axis; in the sixth (harvest) count number of ears refers to the total ears of the plant.) These considerations clearly show the importance of time of application of a spring top dressing of nitrogenous fertiliser. Such a dressing, if applied after the critical date for tiller formation (approximately, let it be supposed, the end of March) may promote the formation of tillers too late to bear ears. It may, nevertheless, valuably stimulate the earlier existing tillers, allowing them to bear heavier ears than otherwise they would. The facts above disclosed, insufficient to settle the questions that here arise, emphasise the need for further knowledge. It may be said that nitrogenous top dressing in spring must remain imperfectly understood until developmental studies of its effects have been made. Census studies on field crops with strips alternately dressed and undressed are in progress.

In the sixth or harvest count population density is the first consideration. The relation between number of seeds sown and number of plants left to harvest cannot be closely determined for, as already explained, precision in seed-counts is impossible. Jethro Tull, by inference rather than direct check, reached the conclusion that, in winter corn, of every ten seeds sown only one survived to be a harvest plant. This statement has been repeated from author to author down to the present day. For the conditions of the present day it is entirely wrong. The evidence of the investigation here recorded, coupled with that of earlier

census studies, suggests that some 60 to 80 per cent. of the seeds sown give plants at harvest. Exceptionally, survival may be much lower, as when very bad seed is used or cold and wetness ruin a piece of non-hardy oats or wheat-bulb fly attack is severe. It may be said, further, that in normal circumstances casualties in wheat plants occur in the early months of the year. Practically the whole of the plants surviving in May contribute to harvest.

§ VII. Comparative Yield in the Four Fields.

Comparison must now be attempted on the basis of yield. As yield reflects all the vicissitudes of growth so must yield-comparison meet the combined difficulties found in earlier comparisons. Tillering, in its full sense, is the key to yield and must therefore be the central feature of comparison. At the outset the nature and significance of tillering must be made clear. Two common misapprehensions have been entertained in connection with tillering. It has been held that yield is not "affected" by tillering: again, that tillering is not a feature of intervarietal importance. These misapprehensions arise from failure to perceive that "spacing" in field crops shows wide but sharply localised fluctuations and through disregard of the developmental aspects of tillering.

The average number of ears per plant at harvest does not reveal the full significance of tillering in relation to yield. Time of commencement of tillering is an important feature. As among the tillers of a plant and as between separately grown populations of one variety, early formed tillers make bigger ears than those arising later. This is the first developmental aspect to be borne in mind when yield-comparison is being made between different fields. Next is the fact that extent of early tillering is an index to "vigour of growth." If, for example, plants are so densely crowded that formation of side tillers is almost suppressed, the main axes of the plants are found to be feebly developed and to form very small ears. Correspondingly the very wide spacing which induces profuse tillering also produces exceptionally large ears on the main axes and chief side tillers. This same association of "vigour of growth" and tillering also appears when fertility or time of sowing or other external growth-factor is varied. It is largely as an index to development that tillering carries significance in relation to the yielding capacities of different varieties. As between separate varieties, similar in general habit and adaptation, early commencement and steady continuation of tillering may be regarded as an index to yielding capacity for it is an indication of ability to develop well under the conditions concerned. The relation between

average number of ears per plant and average size of ear is highly complex. Within limits the two quantities increase or decrease together, their rates of change being governed by many circumstances. If however, because of liberal manuring and spacing, tillering is exceedingly profuse, average ear size may be disproportionately low. This results from an unusual proportion of late-formed tillers being enabled to survive to ear bearing. Their ears, developing late in the season, are small and do not set grain freely. In normal field circumstances such a profusion of tillering does not occur and average ear-size increases with average number of ears per plant.

With these developmental aspects in mind a comparison of yields from the four fields may now be based upon tillering. Field *D* stands out in respect of average number of ears per plant. This superiority in ear formation over fields *L* and *P* (sown with the same variety of wheat) harmonises with the facts recorded for early tillering (fourth and fifth counts). The percentage of early tillers (as found at the fifth count) which bear ears at harvest is shown in Table III (sixth count, line 5). It is very low on field *D*. On this field good conditions of drainage and fertility, coupled with rather low average population density, induced very abundant early tillering. The wastage of tillers was extremely high and, as explained in § V (*supra*), there was accordingly a marked reduction of actual yield below the potential maximum. Tiller survival on field *L* was only slightly higher than on field *D*. There was, however, a much greater average population density and inherent fertility was lower (*vide infra*). As a result early tillering was less profuse but the yield approached more closely to the potential maximum. That is to say, better use was made of the land on field *L* than on *D* by ensuring a more full and more even plant-population. Field *P* shows exceptional tiller-survival, over half the tillers present at the end of April having formed ears. The explanation of this high value probably lies in the extreme poverty of the soil and the paucity of plants. Very few tillers formed (an average of only 1·4 side tillers at the end of April) and population density being low, tiller-survival was high. It was shown in an earlier paper (1) that as between the quintiles of distribution for a field tiller-survival was higher where population density was lower. From the whole series of census studies it appears that in winter wheat some 25–40 per cent. of the tillers present at the end of April normally produce harvest ears. It has already been shown (§ V, *supra*) that on typical field crops reduction of yield through low population density is not counterbalanced by the increased tillering induced by liberal spacing. Low survival rate of tillers largely explains

this fact. It also explains why crops which, like field *P*, start with a "thin plant" and then appear to "gather," ultimately give under-average yield. "Gathering" is the rapid spring tillering which shows up so clearly in a "thin" plant but which does not always ensure a corresponding production of harvest ears.

The correlation between number of ears per plant and number of plants per foot (Table III, sixth count, line 4) is not easy to interpret. At the end of April (fifth count) number of side-tillers showed a well-marked negative correlation with population density. This latter quantity remained constant to harvest but low tiller-survival rate has clearly affected the harvest correlation (ears per plant and population density). Actually the correlation at harvest is not significant for field *D*; for field *G* it is significant but much lower than the earlier (fifth count) value; while for fields *L* and *P* it has remained almost unchanged. It is possible that soil conditions explain the exceptional behaviour of field *D*. On that field, population density was rather low and this, with good drainage and high inherent fertility, has tended to make ear formation more or less equal at different degrees of population density. Earlier, as at the fifth count, population density evidently exercised a fairly well marked control over tillering. But with very favourable growth conditions this control would presumably come into play later than on the other fields. It may, in fact, have become effective only when the "critical time" for tiller formation had passed. Tillers formed after this critical time would bear no ears. Thus spatial influence, having exercised no control over tillering in the period when surviving tillers were being formed, would not be reflected in the harvest results.

It has been pointed out that fluctuation in ear-size (*i.e.* yield per ear) is intimately connected with tillering. Average values for a whole field possess little analytical worth but the marked differences in average ear-size among the four fields point to certain broad conclusions. Fields *L* and *P*, for instance, are strikingly contrasted. They differ little in tillering at harvest and although field *P* carries but half the plants of field *L* it nevertheless has slightly smaller ears. Inherent differences in soil and fertility are thus sharply emphasised. It is evident, too, that on fields such as *P* liberal spacing meets no marked response either in prolificacy of ears or enhanced ear-size. A full and regular plant-population is outstanding among the means by which the maximum output of grain may be wrested from such poverty-ridden land. Field *D*, most prolific in ear formation bears the heaviest ears. In many respects fields *G* and *L* are somewhat similar and they illustrate differences in varietal

habit. Cambridge Browick wheat, on field *G*, with 13·9 plants per foot, has 1·16 ears per plant. Yeoman, on field *L*, with 17·5 plants per foot, produces 1·28 ears per plant. In ear-size, however, Cambridge Browick has a superiority. This comparison supports the conclusions derived from observation of the two varieties under a diversity of conditions. Yeoman always tillers abundantly, save under very poor conditions, but it fails to make the large well-filled ears of which it is capable unless soil fertility is above average. Cambridge Browick characteristically tillers less than Yeoman but its ear-size and filling are less sensitive to soil fertility.

Single plant yield and the yields per foot of row and per acre have their basis in the components already discussed. The range of yields (*vide* Table III) is very wide, but it may be said to reflect in a comprehensible manner the differences in population density and plant development which the fields display. It necessarily reflects soil conditions but these are reserved for the final paragraph.

Average grain-size, expressed in Table III as 1000-corn weight, calls for little comment. The high value on field *G* illustrates the characteristic large grain-size of Cambridge Browick. That field *D* is the lowest of the three Yeoman fields is believed to be in part the result of yellow rust (*P. glumarum*). Traces of rust were found on fields *L* and *P* but field *D* was rather heavily attacked. Unusually heavy incidence of this rust is not uncommon on thinly seeded fields of high fertility. It may be mentioned that grain-size showed no characteristic differences as among the separate quintiles of the fields.

The average number of grains per ear given in Table III has been calculated from ear weight and 1000-corn weight. The high value for field *D*, in contrast with the low value for *P*, suggests that soil fertility is definitely reflected in number of fertile florets per ear. All the values of number of grains per ear are low. But it has been shown in all the census studies that average ear-size in field crops is lower than casual eye impressions suggest. Correspondingly, the average number of ears per plant at harvest appears, in representative field crops, to vary from about 1·2 to 1·8, a decidedly lower value than is commonly supposed.

§ VIII. COMPARATIVE SOIL CONDITIONS.

In § VI (*supra*) attention was called to two "critical periods" in crop life:

(1) The critical period for tiller formation. As an average result, for a population of plants, all side-tillers which arise after this time die in early summer and so fail to contribute to harvest yield.

(2) The critical period of spatial influence. Up to this point in crop life population density and tillering show no correlation. Thus, for the range of densities found in typical field crops, spacing does not limit plant development prior to the critical period. After this period density and tillering show the characteristic negative correlation.

From the data here available it is impossible to determine the precise chronology of these two critical periods. The inference is (*vide* § VI *supra*) that on all four fields both periods occur towards the end of March. Other census and plot studies have indicated the same broad conclusion. It has been pointed out that precise knowledge of the critical period of tiller formation is essential to the proper use of nitrogenous fertilisers in spring. But the essential importance of the two critical periods lies in their appearing, on present evidence, to be more or less synchronous. If they be effectively synchronous then inter-plant spacing is not a limiting factor to tillering during the span of time in which fertile or ear-bearing tillers are formed. Weather conditions undoubtedly react upon the critical periods, but, with present limitations to knowledge, the reaction cannot be brought into account. Apart from weather, the production of fertile tillers must be controlled primarily by soil conditions. Thus, whatever the subsequent influence of liberal spacing, final yield is largely pre-determined by the influence of soil conditions on plant development up to about the end of March. It is most improbable that any rigidity attaches either to the chronology or nature of either of the critical periods. A favourable coincidence of weather conditions or a timely application of fertiliser may defer the critical period of tiller formation. The synchronisation of this period with the critical period of spatial influence may be common only over a limited range of population density. It may be said, however, that the pre-determining effect of soil conditions upon yield, as reflected in early plant development, is a fundamental factor in yield-analysis. In particular, such a pre-determination bears directly upon the popular idea that "thin places" in a field or thin fields as a whole are likely, by "gathering" or profuse tillering, to give a normal yield. If the soil conditions—fertility, drainage, etc.—are inherently poor, tillering is not likely to show marked response before the critical period of tiller formation. Fields *D* and *P* offer an interesting illustration of this (field *G* was sown with a different variety and on field *L* spring harrowing made the March tiller-count impossible). Population density was approximately the same on both fields. In early March neither field showed any correlation between population density and tillering (Table III, fourth count, line 4). The great difference in

soil conditions was reflected in the average numbers of tillers per plant, viz. field $D = 1{\cdot}2$ and $P = 0{\cdot}6$. Increase in tillering during April emphasised further the difference in soil conditions (*vide* fifth count). A large proportion of April-formed tillers died before harvest. But, as seen in the sixth count (line 2) the superiority of field D in early tillering was projected into harvest fruition. Predetermining influence is also illustrated by comparisons of field L with fields D and P. In these comparisons regard must be paid to the greater density of population of field L and to the soil conditions of the fields (*vide* § II, *supra*). The principle of predetermination here outlined, carries an important practical implication. On land of low fertility and bad drainage, exemplified by field P, localised irregularity or general paucity of plants must very directly limit the yield. It is on such land, in particular, that careful seeding and an adequate seed-rate are of importance.

To assess the relative influence of soil on the four fields, allowance must be made for differences in population-density. This may be done by making comparisons among aggregates of foot-lengths having specified plant-populations. Extremes of density must be disregarded as their frequency of occurrence is low. It is convenient to recognise the following density gradations for fields D, G and L—7 or 8 plants per foot, 9 or 10 plants per foot, and so on to 19 or 20 plants per foot. In the case of field P values above 15–16 must be omitted. The actual yields for the density-gradations are shown by the points plotted on Fig. 1. On the same diagram are drawn the lines of regression of yield on population density. The equations of these lines have been given in § V (*supra*). In general trend the actual density-gradation yields lie fairly close to the regression lines. Thus, in adducing general evidence as to soil conditions, reference may be made to these lines. It will be appreciated that regression lines are valid only over the range covered by actual observations. Even within this range they are not reliable at the upper and lower extremes of population-density.

The unfavourable soil conditions of field P are strikingly shown. At every gradation of population-density its rate of yield is markedly lower than the rates for the other fields. That productivity is more or less at a level for fields G and L is in harmony with what is known of inherent soil condition and recent agricultural treatment. Field D is outstanding. Its relation to fields L and G at low population-density cannot, unfortunately, be deduced from the available data. The distinguishing feature is the steep slope of the line of regression. This slope, measured by the coefficient of X (number of plants per foot) in the regression equation,

indicates the rate of increase of yield per foot with increase in population-density. The high rate of increase conforms with the excellent soil conditions by which this field is known to be distinguished from the others.

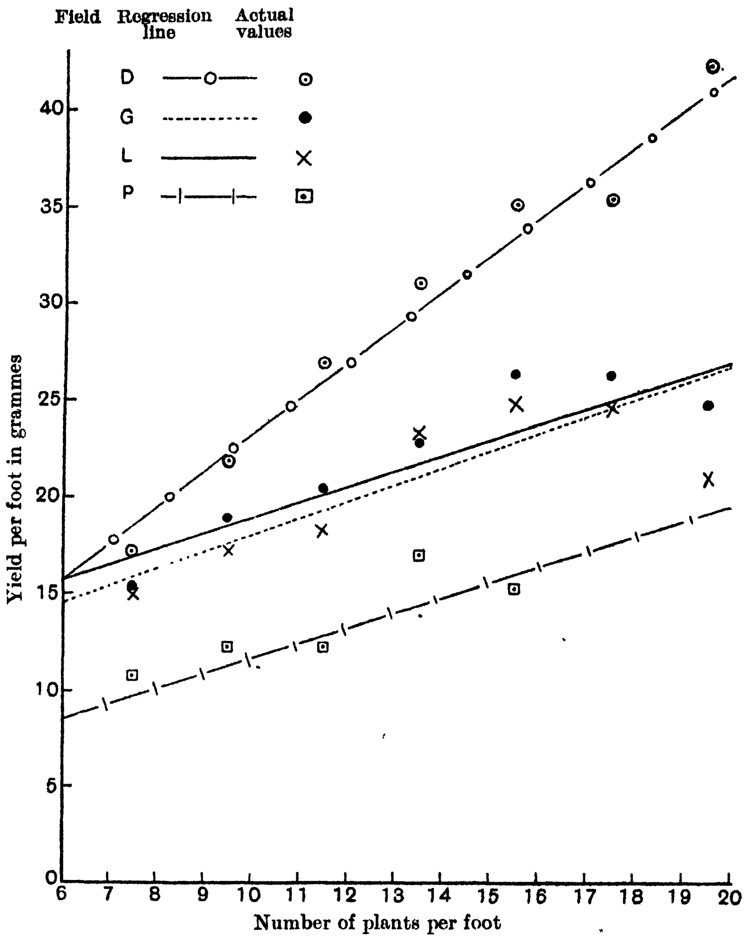


Fig. 1. Regression lines of yield on plants per foot, Fields *D*, *G*, *L* and *P*, 1926–27.

Some 14 plants per foot is a common average population-density on typical well-managed wheat fields. For this the corresponding rates of yield are seen to be: field $D = 30{\cdot}5$: $G = 21{\cdot}5$: $L = 22{\cdot}2$: $P = 14{\cdot}8$ (grammes per foot), *i.e.* $D = 69{\cdot}5$: $G = 49{\cdot}0$: $L = 50{\cdot}6$: $P = 33{\cdot}8$ (bushels per acre). These values may be regarded as a reasonable estimate of the soil conditions or productivity of the four fields.

It has been possible to effect no more than an outline-comparison of development, yield, and soil conditions. This, however, has served to establish the nature of the influence of soil conditions upon the stages of growth and thus upon final yield. The considerable economic importance of a regular plant-population as a factor governing yield has been made manifest with respect to four widely different sets of conditions. Marked reduction below maximum potential yield has been traced in all the fields to localised low values of population-density. For two fields, *D* and *P*, a deficiency in average density has involved heavy sacrifice of yield. In both cases the causes of deficiency, although preventable, were of a kind not unfamiliar in farming practice. Census-studies, on developmental lines, may perhaps be said to offer one practicable means towards the analysis of yield in field crop.

The co-operation of Mr C. B. Taylor, Colonial Office Scholar, who assisted at all stages of the experimental work, is very gratefully acknowledged.

SUMMARY.

In any field of corn the population-density or number of plants per unit length of row is very fluctuating. Accidental circumstances may result in considerable stretches being empty or thinly populated. Quite apart from this, the population of successive short lengths is sharply and characteristically inconstant. Where plants are few tillering is profuse and there is thus a tendency towards constancy in yield per unit length of row. Specific ascertainment has, in earlier experiments, suggested that the tendency is by no means marked. In consequence fluctuation of population-density in the sense here used, reduces yield in typical field crop substantially below the potential maximum appropriate to the soil and other circumstances. From short lengths of row, low in plant-population, yields are low. In aggregate these sparsely populated lengths are a feature of considerable economic importance.

It was decided to repeat the earlier studies using the "census of an acre" method already described (1). In this the unit of observation is a one-foot length of a row of plants. Four wheat fields widely different as to soil and standard of husbandry were brought under observation. Thus the investigation was given an agricultural representativeness. Yield is an ultimate expression of plant development and yield analysis must

have a developmental basis. Accordingly, periodic determinations of population-density, and of development as judged by tillering, were made from sowing to harvest on all the fields.

Whatever the causal relationship between population and yield upon a short length of row, soil conditions must be expected to influence the yield. Special consideration has had to be given to the possibility that soil conditions, far more than population-density, are responsible for high fluctuation in yield per unit length of row.

Many causes are known to contribute to fluctuation in population-density. The influence of one group of these is measured by the fluctuation of the seedling population. Within this group are the inherent mechanical efficiency of the drill for even distribution of seed and the influence of tilth on drill action. In a first record of work on the four fields (4) the action of the drill is fully discussed. It is concluded that deposition of seed on short lengths of row is highly irregular. This reflects inherent drill defects far more than disturbances in drill action brought about by tilth irregularity. The outstanding defect of the (cup) drill is inconstancy, from moment to moment, of the load of seed delivered into the spouts by any and every seed-cup.

The characteristic occurrence of sharply localised fluctuations in density from point to point along the rows of plants, was fully confirmed. In illustration of its nature the data from the most evenly sown of the four fields may be noted. Aggregating unit lengths (one-foot) of row on the basis of population-density, it was found that equal one-fifth parts (aggregates) of a typical acre had the following average numbers of plants per foot at harvest: 9·3: 13·5: 16·7: 20·9: 27·0.

Many factors, among them damage by winter, by diseases and by pests, superpose their effects on the initial fluctuations of population-density induced by irregular seed distribution. Evidence from developmental studies on all four fields shows, however, that at all stages of growth the density fluctuation must be regarded as essentially the outcome of irregular drill action.

The influence of fluctuation in population-density upon yield per acre is next considered. All the samples from an acre may be divided into five equal frequency groups on the basis of the number of plants per foot at harvest. These groups, or quintiles of distribution, correspond, of course, to areas of one-fifth of an acre. As an illustration the data for one of the fields may be quoted:

Average number of plants per foot for the quintile (*i.e.* density aggregate): 5·0; 9·2; 12·6; 16·1; 21·2.

Average yield per foot for the quintile (grammes): 12·4; 21·7, 28·5; 35·9; 42·3.

Equivalent in bushels per acre: 28; 50; 65; 82; 96.

These marked differences in yield-rates upon one and the same acre are shown to be associated with corresponding variations in tillering and ear size in the manner which usually characterises the influence of spacing upon growth.

A different presentation is afforded by measurement of correlation. Between number of plants per foot and yield per foot the coefficients of correlation for the four fields ranged from + 0·6 to + 0·8. Regression equations, derived from these coefficients, indicate that for unit increase in number of plants per foot the rate of increase in yield per acre would be, for the fields in turn (bushels) 4·2; 2·0; 1·8; 1·7.

Specially devised tests were made of the possibility that fluctuations in yield per foot might be attributable rather to soil conditions than to inconstant population-density. This possibility was excluded by the results of the tests. That yield and population-density on short lengths are closely related is to be regarded, therefore, as of the nature of cause and effect.

Census counts were made at intervals between sowing and harvest. From these may be traced the developmental history of the crop on the four fields. Of the seeds sown, some 60-80 per cent. appear to survive and give harvest plants. Plant-loss occurs almost wholly before the month of May. Correlations between population-density and tillering on short lengths of row reveal an interesting aspect of growth. In early March the correlation is not significant. By the end of April it has a marked negative value. Up to some "critical period of spatial effect" therefore, tillering is not influenced by population-density. From these present, and from other studies, this critical period is inferred to be at about the end of March. It is not likely to be common to all spacings but may be regarded as the effective critical period for field crops of winter wheat.

New tillers continue to arise as late as May in normal years. The tiller counts were not made, however, beyond the end of April. Of the tillers formed up to this time a large proportion dies in early summer. On typical fields only some 25–45 per cent. of April tillers survive to harvest and form ears. Thus there must be in effect, a critical period of tiller-formation. Tillers arising after this period normally die out. It appears probable that this second period, like the first, falls towards the end of March. That the two critical periods chance more or less to synchronise

is of considerable practical significance. The fact brings out the great pre-determining effect of early-development, as seen in early tillering, on yield. Juvenile development, prior to the critical period for tillering, essentially reflects soil conditions. It may, however, be influenced by early applications of nitrogenous fertiliser. The effective use of such fertilisers thus clearly depends on a knowledge of developmental history and especially of the two critical periods. From the four fields, differing widely in soil and treatment, clear illustrations may be drawn of the principles here outlined.

Tillering in mature plants is not an attribute of biological importance. It is a final expression of the response of growth to many external factors among which population-density is important. But a developmental study of tillering for a range of population-densities serves to connect final yield with soil conditions and other growth factors. This connection is traced out for the four fields. It is shown that during the stages of crop life, development reflects the circumstances of soil, population-density and agricultural treatment. An analysis of harvest populations serves, finally, to connect relative soil and other growth factors with ultimate yields.

Developmental studies, on census of an acre lines, appear to offer a means of analysing the yield of field crop by assessing the influences of the principal factors of growth.

APPENDIX.

On Reliability of Result.

There are two essential considerations. On every field an acre was selected. This was brought under observation by a series of counts each based upon one hundred samples or one-foot lengths of row. It is necessary to consider whether the samples were truly representative of the acre. Next, for the separate fields, the 100 samples were aggregated in various ways, and mean differences, correlations etc. were evaluated. The statistical significance of these quantities is the second consideration.

Special precautions were taken in connection with the representativeness of the 100 samples. On two of the fields a pair of samples, adjoining one-foot lengths, was drawn at every sampling point. The members of such a pair are designated α and β. Thus for these fields all observations are duplicated, *i.e.* represented by α and β series, each series being 100 samples. For all counts, the differences between α and β results are not statistically significant. This evidence is, of course, valid only if the α and

β values show no correlation. Absence of correlation has been clearly established. Distribution of the 100 samples upon an acre raises certain questions of reliability. The principle was to ensure drawing the same number of samples from the work of every coulter of the drill; and further to distribute the samples at a constant interval apart along and across the field. Thus distribution was not random. The case for random distribution is involved. It was, upon consideration, judged most practicable and in general best to adopt the systematic dispersion of samples as described above. Position in the row was determined by pacing. A peg, marking the beginning of the sample length, was inserted in the row immediately opposite the toe of the pacer's foremost foot. In this way bias was avoided.

All coefficients of correlation were tested by the usual test of significance. Values of yield per foot, per plant and per ear, as also of ears per plant for quintiles and other aggregates of the 100-sample distribution may be tested in two ways. The standard error of difference may be evaluated, and evidence so obtained may be said to justify the use to which the various differences have been put. Further, the steady trend of values from quintile to quintile, characterising the data from all four of the fields, is of itself supporting evidence.

REFERENCES.

(1) ENGLEDOW, F. L (1926). "A Census of an Acre of Corn (by Sampling)." *Journ. Agric. Sci.* **16**.

(2) (1926). "A Census of an Acre of Barley." *Journ. Roy. Agric. Soc.* **87**.

(3) HUNTER SMITH, J. and WILLIAMS, RHYS H. (Aug. 1927). "A Census of an Acre of Roots." *Journ. Min. Agric.* **34**.

(4) ENGLEDOW, F. L. (1928). "Investigation on Yield in the Cereals. IV. The Action of the Seed Drill." *Journ. Agric. Sci.* **18**.

(*Received January 19th*, 1928.)

THE AMMONIACAL NITROGEN OF PEATS AND HUMUS SOILS. PART II.

By J. C. B. ELLIS, M.A. and C. G. T. MORISON, M.A.

(*School of Rural Economy, Oxford.*)

In a previous paper[1] published in this *Journal*, an attempt was made to draw some distinction between the sources of ammoniacal nitrogen to be obtained by distilling peats with magnesia. It was indicated that such nitrogen might be derived either from hydrolyis by the magnesia with which the peat was distilled (see method), or from ammonia or ammonium compounds absorbed by the peat. It was proved that a considerable quantity of such nitrogen compounds could be removed by extraction with water, which showed that the soil solution in peat contains ammonia or ammonium compounds which are in equilibrium with the same substance absorbed by the colloidal bodies in the humus of the peat.

As the amount of such nitrogen compounds differed widely for different peats, and also for the same peats taken from different depths, it appeared desirable to make further direct distillations and water extractions of peats, both in the wet (*i.e.* as recovered from the peat bog) and in the air dried condition in order to see if the drying of the peat had any effect on the total amount of nitrogen, as determined by direct distillation, or on the amount capable of removal by water extraction.

The methods employed have been essentially the same as those used in Part I of this paper.

Table I shows some results for samples of peat taken from the surface of the bog, and from depths of 3 ft. and 6 ft. respectively.

On consideration of the figures for direct distillation, it will be seen that the drying of the peat has had a considerable effect upon the ammoniacal content of each peat.

In some cases the figure for the dried peat is higher, and in other cases it is lower, and it is reasonable to suppose that the irregularity of these results is due to at least two causes.

The drying of the peat may have resulted in some further decomposition of the unstable nitrogen compounds present, and this, if the resulting compounds were not volatile, would result in an increase in the ammonia content.

The drying operation may also cause non-reversible changes in the

[1] Morison and Ellis, vol. VIII, pt. I, p. 1.

Table I. *Ammoniacal nitrogen per cent.*

	Direct distillation		Water extraction		$\frac{\text{Water extraction}}{\text{Direct distillation}} \times 100$	
	Wet	Dry	Wet	Dry	Wet	Dry
Corrour:						
Surface	·0139	·0261	·0039	·0215	27·8	72·2
	—	·0296	—	·0168	—	—
	—	·0285	—	·0225	—	—
Three feet	·0442	·0184	·0163	·0204	36·9	113·8
	—	·0189	—	·0222	—	—
	—	·0186	—	·0210	—	—
Six feet	·0171	·0097	·0103	·0050	60·2	68·2
	—	·0075	—	·0061	—	—
	—	·0080	—	·0061	—	—
Killeen:						
Surface	·0335	·0102	·0087	·0092	25·8	86·8
	·0302	—	·0085	·0085	—	—
	·0362	—	—	—	—	—
Three feet	·0117	·0120	·0091	·0142	72·3	123·5
	·0131	·0111	·0096	·0142	—	—
	·0140	—	—	—	—	—
Six feet	·0334	·0173	·0159	·0211	46·9	120·8
	·0324	—	·0168	·0207	—	—
	·0346	—	·0144	—	—	—
Knockballyboy:						
Surface	·0041	·0053	·0025	·0033	54·6	81·7
	·0047	·0051	·0023	·0052	—	—
Three feet	·0088	·0113	·0085	·0066	94·3	55·2
	·0088	·0108	·0081	·0056	—	—
Six feet	·0089	·0088	·0099	·0069	113·8	70 6
	·0077	·0083	—	·0056	—	—
	·0094	—	—	—	—	—
Castlegrove:						
Surface	·0115	·0057	·0033	·0046	28·7	80·7
	·0115	·0052	—	·0042	—	—
Three feet	·0109	·0099	·0030	·0042	37 0	47·4
	·0115	·0095	·0057	·0050	—	—
	·0129	—	—	—	—	—
Six feet	·0037	·0078	·0021	·0042	39·6	61·0
	·0053	·0081	·0021	·0055	—	—
	·0069	—	—	—	—	—
Meeneen:						
Surface	·0240	·0235	·0078	·0119	30·0	52·8
	·0250	·0224	·0069	·0123	—	—
Three feet	·0064	·0104	·0039	·0071	44·0	73·2
	·0097	·0101	·0029	·0079	—	—
	·0071	—	—	—	—	—
Six feet	·0226	·0147	·0056	·0109	26·2	68·5
	·0204	·0171	·0056	·0112	—	—
	·0211	—	—	—	—	—

colloidal organic matter decreasing its absorptive power, and this would also cause an increase in the amount of ammonia removable by subsequent distillation with magnesia.

On the other hand, it is possible that a loss of volatile constituents may take place causing a drop in total ammonia. The nature of the peat,

and its original content of ammonia, will determine which of these factors predominates.

It is noticeable that those peats in which the content of ammonia is high in the original wet state show generally a considerable drop when the peat is dried.

Further information on the course of the action on dehydration is obtained by a consideration of the figures for direct distillation with magnesia, and for water extractions both in the wet and dried state. These figures are given in Table I.

The figure in the last two columns for wet and dried peat respectively expresses the water soluble ammonia as a percentage of the total ammonia obtained by magnesia distillation.

On comparing these percentage figures for wet and dried peats, those for the dried peat show an increase over those for the wet in all cases but one. This increase is in some cases very considerable, showing that the effect of dehydration is to render a very much larger amount of the total ammonia present soluble in and removable by water. This can only be brought about, in the authors' view, by a change, which may or may not be reversible, in the character of the organic colloid constituents, and their power of absorption.

It has been shown by Mr J. L. Steenkamp in work carried on in this laboratory, and shortly to be published, that in some cases of dried soils the degree of saturation of the soil colloids in exchangeable bases is thereby increased, and it is suggested that the observed increases in water soluble ammonia are due to a similar cause. The concentration of ammonia in the water extractions depends upon the degree of saturation of the organic colloids.

Further confirmation of this view is afforded by a consideration of the results given in Table I for samples of peat taken from depths of three feet and six feet respectively.

These results agree in the main with the results for surface peats. An interesting exception is afforded by the peat from Knockballyboy. This was a neutral peat while all the others were acid to a greater or lesser extent.

In all the other cases the figures for $\frac{\text{Water Extraction}}{\text{Direct Distillation}} \times 100$ are larger in the peats which had been dried before extraction.

It is suggested that the increase in water soluble ammonia observed on drying the peat is due to a decrease in the absorptive power of the colloid, and a consequent increase in the concentration of ammonia in the solution.

This change in the character of the organic colloids of the peat may be one which is reversible, in which case the peat should recover its power of retaining ammonia on standing with water.

The following experiment indicates that some recovery occurs. In this experiment dried peat was shaken with water for different periods of time, filtered, and the ammoniacal nitrogen in the filtrates determined. If the absorptive colloidal properties of the peat are wholly, or in part, restored, a diminution in the amount of ammoniacal nitrogen obtained from the filtered extract would result, because some of it will have been again absorbed by this colloidal material, leaving a smaller amount in the solution. The peat employed was from Meeneen and gave the following results:

Time in hours	1	1	15	15	65	65
% Ammoniacal nitrogen	·0375	·0375	·0187	·0218	·0187	·0187
Time in days	7	7	10	14	14	
% Ammoniacal nitrogen	·0187	·0187	·0156	·0156	·0156	

The above table shows that there is a marked decrease with time in the amount of ammoniacal nitrogen extracted, and that after a time equilibrium is reached, and no further diminution in concentration occurs.

It was shown that this diminution could not have been due to nitrification before or after filtration by the fact that treatment of the extract with a suitable reducing agent produced no further ammonia.

It was concluded therefore that on shaking dried peat with water a partial recovery of colloidal properties takes place, such that the absorption shown by the wet peat increases with prolonged contact with water until a constant figure is reached.

SUMMARY.

1. When a peat, as obtained from the bog, is dried, considerable changes occur in the amount of ammoniacal nitrogen removable by distillation with magnesia under reduced pressure.

2. Removal of water causes a relative increase in the amount of ammonia extractable by water. This is due to a reduction in the absorptive colloidal properties of the peat.

3. A partial recovery in the absorptive power takes place on prolonged contact with water.

(*Received January* 21*st*, 1928.)

DYE ADSORPTION BY HYDROUS ALUMINA IN SOILS.

By H. H. CROUCHER, B.Sc.
(Imperial College of Tropical Agriculture, Trinidad, B.W.I.)

(With One Text-figure.)

I. Introduction.

Among the methods used in attempts to measure the amount of colloidal matter in soils, those depending on the adsorptive properties of colloids have received considerable attention. Dyes have been mainly used as the adsorbed substance because of their relative large adsorbability by soil colloids, and because of the comparative ease with which small concentrations of dyestuffs can be estimated. The dye method has not proved altogether satisfactory, however, and there is much dissension on its merits among various writers. Thus Rohland (1) definitely states that the capacity of soil for adsorbing dyes gives trustworthy indication of the amount of colloidal matter it contains, while Graf zu Leiningen (2) draws the opposite conclusion.

A study of the literature dealing with dye adsorption shows that the general failure of the method is due to variations in the following factors:

(*a*) The chemical composition of the colloidal material.

(*b*) The presence of previously adsorbed ions.

(*c*) The hydrogen-ion concentration of the soil suspension.

(*d*) The nature of the dye, and its concentration in the suspension medium.

The influence of these factors may perhaps best be explained if it be assumed that soil colloids possess amphoteric properties, and that each of their chemical components exhibits a distinct isoelectric point. The probability that this is the case has been urged by Hardy (3). He points out that the hydrous oxides present in soil colloids may behave as amphoteric electrolytes and dissociate in either of two ways, depending on the relative concentration of hydroxyl and hydrogen-ions in the surrounding medium. The dissociations for hydrous alumina, for example, may be indicated thus:

$$(1)\quad Al_2O_3{\cdot}xH_2O \rightleftarrows Al_2O_3{\cdot}xH^{\cdot} + x(OH)';$$

$$(2)\quad Al_2O_3{\cdot}xH_2O \rightleftarrows Al_2O_3{\cdot}xOH' + xH^{\cdot}.$$

At the isoelectric point, ionisation and adsorption will be least. The isoelectric point of hydrous alumina has been found to be pH 6·5. At a lower pH value than this excess of hydrogen-ions will favour reaction (1), and the hydrous alumina will assume a positive charge. Similarly, a reaction more alkaline than the isoelectric point will favour reaction (2), and the hydrous alumina will assume a negative charge.

Presumably these reactions occur only at the surface molecules of the hydrous alumina particles, the internal molecules remaining unchanged, but the particles as a whole acquiring an electric charge. In an acid medium the hydrous alumina will therefore tend to act as a weak base, and will have a greater tendency to adsorb negatively charged rather than positively charged particles, whilst in an alkaline medium, it will tend to act as a weak acid, and will have a greater adsorbing power for positively charged particles. Hence, if an acidic dye (that is, a dye producing hydrogen ions and negative dye ions) be added to a suspension of hydrous alumina, there will be a much greater tendency for the alumina to adsorb the negatively charged dye ions when the suspension has a pH value less than 6·5. Similarly, if a basic dye be added it should be adsorbed chiefly in those media whose pH values are greater than pH 6·5, where the hydrous alumina is acting as a weak acid and is negatively charged.

Hydrous ferric oxide appears to bear a close resemblance to hydrous alumina. It may be amphoteric, and, in all probability, has an isoelectric point about pH 6·5(3). Hydrous ferric oxide should presumably therefore adsorb dyes in a similar way to hydrous alumina.

Hydrous silica is also probably amphoteric, but the markedly acidic properties it possesses indicate that the isoelectric point must be well on the acid side of neutrality(3). Under normal soil conditions presumably it reacts as a weak acid, and should adsorb mainly basic dyes.

The remaining components of the soil colloid complex may be classed as hydrous alumino-silicates and hydrous ferro-silicates. There is strong evidence that they also may act as ampholytes with widely divergent isoelectric points. Their individual reactions towards dyes may therefore vary considerably.

The following results are readily explained by application of the isoelectric theory.

(a) Influence of the chemical composition of the soil colloids.

The colloidal material separated from any one soil may be regarded as a mixture of several different chemical substances. Each chemical component will have a particular capacity for adsorbing dyes.

Way (4), in 1850, noted the significance of the chemical composition factor, but little attention has been paid to it by subsequent workers. Warington (5) found that the adsorbing capacity of ferric hydroxide for potassium or ammonium hydroxide was three times greater than that of aluminium hydroxide. Tschermak (6) showed that the various silicic and alumino-silicic acids behaved differently towards Methylene Blue. Ashley (7) could obtain a relationship between plasticity and adsorption of Malachite Green and Brilliant Green only for clays of common origin, that is, clays which contain the same chemical components in approximately the same proportionate amounts. The results obtained by Beaumont (8) from experiments with some artificially prepared colloids, and with some soil-forming minerals, are in accordance with the isoelectric theory. Beaumont found that the basic dye, Methylene Blue, was strongly adsorbed by colloidal silica but not by colloidal ferric oxide in neutral suspension, while the acidic dye, Diamine Sky-blue, was adsorbed by ferric oxide but not by silica. He accounted for the failure of Diamine Sky-blue to show significant differences between soils, by supposing that the ferric hydroxide contained in them had already adsorbed organic humus. It appears more probable, however, that Beaumont's soils contained very little ferric hydroxide, but considerable silica, which does not react with Diamine Sky-blue. Beaumont proceeded to use the dye adsorption method for determining the effects of air-drying on certain soils. Since he used the same soil throughout each series of experiments, this procedure should give comparable results.

The adsorptive capacity of each colloidal component of a soil probably varies with its state of hydration. Thus Tschermak (6) was able to trace a relationship between the adsorptive power and the number of hydroxyl groups present. The amount of dye adsorbed by hydrous alumina certainly varies according to the method of its preparation.

It is thus possible to conceive two soils containing the same total amount of colloidal material, but having different dye adsorptive capacities, for example, a soil consisting mainly of hydrous silica will have a different adsorptive capacity from a soil consisting of alumino-silicates, although the total amount of colloidal matter present in each may be identical.

(*b*) *Influence of the presence of previously adsorbed ions.*

The effect of previously adsorbed ions on dye adsorption has seldom been considered. Wood and Wooller (9), however, found that the dye adsorbing property of hydrous alumina, while not affected by sodium

sulphate, was altered by sodium phosphate and by potassium citrate. Its behaviour towards dyes was largely decided by the presence of acidic impurities. Bancroft (10) has also pointed out that previously added electrolytes affect the adsorbability of a dye. Theoretically therefore, the adsorptive capacity of the colloidal component of a soil should be altered by causing it to adsorb certain simple ions before introducing a dye. Since soils possess adsorbed ions in widely varying amounts, it might be advisable as a preliminary to their examination by dye adsorptive methods, first to leach them thoroughly with sodium chloride, or to submit them to prolonged electrodialysis. This would yield "sodium clays," or "acid clays," in which the adsorbed simple ions have similar identity.

(c) *Influence of the hydrogen-ion concentration of the soil suspension.*

It follows from the isoelectric theory that the dye adsorbing capacity of any particular soil colloid is not constant over a range of hydrogen-ion concentration. The amount of dye adsorbed at any given *p*H value should depend on the magnitude of the difference between this *p*H value and the *p*H value representing the isoelectric point of the colloid. It is evidently impossible to decide an optimum hydrogen-ion concentration for the comparison of all soils.

Wilkinson and Hoff (11) considered that the differences in the amounts of dye adsorbed by a soil at various hydrogen-ion concentrations were due to base exchange between the dye and the colloidal particles. By first saturating the adsorptive capacity of soils with hydrogen or hydroxyl-ions, they obtained maximum base exchange with basic Methylene Blue and acidic Diamine Sky-blue respectively. As they used relatively high concentrations of acid and alkali, their results were undoubtedly due to a mass action or base exchange effect rather than to any amphoteric properties of the colloids.

(d) *Influence of the nature of the dye and its concentration in the suspension medium.*

The variation in adsorption with the nature of the dye used is, of course, closely related to the composition of the adsorbing soil colloid. The isoelectric theory implies that a given soil may adsorb two dyes in widely differing amount, for example, a neutral soil, containing chiefly hydrous alumina or hydrous ferric oxide, should adsorb a basic dye in greater amount than an acidic dye. Testoni (12) supported this view by his discovery that hydrous silica adsorbs only basic dyes, hydrous alumina only acidic dyes, while kaolin adsorbs either dye. Bechold (13)

similarly found that basic Methylene Blue is adsorbed by Fuller's Earth, permutite, silicic acid and charcoal, while the acidic dye, Trypan Blue, is only adsorbed by charcoal and by ferric hydroxide. Furthermore, Sjollema (14) found that, whereas Methyl Violet is generally adsorbed to the same extent by soils no matter what their composition, other dyes, such as Naphthol Yellow, Alizarin, and Congo Red, appear to be more selective. Finally, Rohland (15) suggested that complex dyes are only adsorbed by colloidal clay if they are themselves of colloidal nature, but not if they are crystalloidal. He considered that this difference might furnish a method for distinguishing between various types of dye-stuffs. Thus, dyes derived from the triphenyl-methane series are readily adsorbed, while those containing nitro- and azo-groups are only adsorbed with difficulty.

Ashley (7) has applied results obtained by Cameron and Patten to demonstrate that clay colloids follow the same rule as artificial colloids, namely, that with increasing concentration of dye in the suspension medium, a maximum adsorption capacity is reached. Hanley (16) showed that, in order to obtain comparable results with Methyl Violet, the final equilibrium concentrations of dye in contact with soil must be identical.

Gile, Middleton, Robinson, Fry, and Anderson (17) have evolved the most satisfactory dye adsorption method yet devised. They determine the amount of colloidal matter present in a soil by measuring first the adsorptive capacity of the total soil, and then determining the adsorptive capacity of a sample of colloidal matter separated from it by centrifuging. Malachite Green, ammonia, and water vapour were used as the adsorbed substances. The colloids from different soils examined by them varied largely in their adsorptive capacities, especially towards the dye. The chief objections to this method are, (*a*) it necessitates a definition of the limiting size of a colloidal particle, (*b*) it is difficult to extract representative colloidal material by centrifuging, and (*c*) the adsorptive capacity of a soil colloid may be increased during the centrifuging process. The last named result might be due to the progressive removal of adsorbed ions.

It would appear to be more satisfactory to compare soils by measuring some representative physical property of the soil, rather than by measuring the properties of some arbitrarily defined component fraction. Since the essential properties of soil are largely dependent on its capacity for adsorbing ions, a measure of the total adsorptive capacity should be sufficient for most purposes of comparison. Until the factors which have

been mentioned can be controlled, however, comparative values for adsorptive capacity cannot be obtained by the use of dyes.

II. The Identification of Hydrous Alumina in Soils.

No direct method has yet been evolved for the identification of free hydrous alumina in soils. In its detection, drastic treatment of the soil liable to decompose the more unstable alumino-silicates present, must be avoided. A selective test is therefore required which can be applied without having first to remove soil components other than alumina. The use of suitable dyes, which, because of their selective adsorption at different hydrogen-ion concentrations, might demonstrate the presence of hydrous alumina by revealing its isoelectric point, ought to furnish such a test.

Experimental. Preliminary experiments were made with hydrous alumina suspensions in water. These were prepared by precipitating the hydroxide with ammonia from aluminium chloride solution, filtering, washing with hot water, and then boiling a suspension of the precipitate with gradual addition of dilute hydrochloric acid until peptization occurred. By regulating the time of boiling and the amount of acid added, the degree of hydration of the alumina could be varied. The colloidal solutions were dialysed in parchment bags against running water until excess of free acid had been removed.

Twenty-five cubic centimetres of suspension were pipetted into each of a series of test-tubes. Attempts were made to buffer the suspension to various pH values ranging from 2·0 to 9·5 using, first of all "Universal Buffer" and later, simpler buffer solutions. It was found, however, that the acetate-ion or phosphate-ion present in the buffer solutions used appreciably reduced the adsorption of dye by hydrous alumina, probably owing to preferential adsorption of these ions. Finally, the pH values of the suspension were regulated by careful addition of dilute hydrochloric acid or very dilute sodium hydroxide solution. The procedure is somewhat clumsy and laborious as the content of each tube has to be tested colorimetrically to confirm its pH value. After some practice, however, a series of tubes containing hydrous alumina at various pH values, differing approximately by 0·5 of a pH unit, could be quickly set up without difficulty. A very definite buffering action occurred at approximately pH 4·0–3·5, due to the dissolving of the alumina. In many cases, non-peptized alumina was used and found to be equally serviceable in the dye adsorption experiments.

From the original series, two series were found by taking 10 c.c. portions from each tube. To each tube of one series was added a certain

amount of 0·1 per cent. solution of an acidic dye (measured in drops from a 1 c.c. pipette), and to each tube of the other series, an equal amount of a basic dye solution. After allowing to stand for about an hour with shaking at intervals, the intensity of the dye colouration in each tube was noted, and an approximate curve drawn of the variation of intensity of colour with the hydrogen-ion concentration. When two apparently satisfactory dyes, one acidic and the other basic, were found, they were mixed and added to the tubes together. It was often found more satisfactory, however, to add the dyes separately, especially when soils were being examined, as the relative amount of the two dyes adsorbed varied considerably with different soils. By separate addition, the concentrations of the dyes could be regulated to suitable values. More than fifty dyes were examined. The qualifications for ideal dyes are:

1. They must be soluble in solutions of *p*H values varying between 2·0 and 9·5.

2. They must be readily adsorbed by hydrous alumina, but not excessively.

3. The two dyes and their mixtures, must have the same depth and shade of colour throughout the whole *p*H range. Thus no indicator dye is admissible.

4. They must be fairly "fast," that is, they must not fade or change colour too quickly on standing in either acid or alkaline solution. Some dyes, for example Cotton Blue, tend to change colour on standing in alkaline solution.

5. The two dyes, one acidic and the other basic, must have intense and widely contrasting colours, for example, red and blue, or blue and yellow.

The red and blue pair seems to furnish a very satisfactory combination, but if a really intense yellow could be obtained perhaps a yellow and blue pair would be even better. Unfortunately, however, very few yellow dyes seem to be sufficiently adsorbed by hydrous alumina[1].

[1] The following dyes were found to be adsorbed only to a slight extent by hydrous alumina: Aniline Yellow, Brilliant Green, Basic Fuschin, Crystal Violet, Gentian Violet, Indigo, Light Green, Magenta, Malachite Green Oxalate, Malachite Green Chlorides, Methyl Green, Methylene Blue, Methyl Violet, Thionine Blue, Victoria Blue, Metanil Yellow, Monochrome Yellow 2 *R*, Naphthol Yellow, Orange *G*, Patent Blue, Tartar Yellow *FS*, Tropœolin *OO* and Tropœolin *OOO*. The following were too highly adsorbed: Night Blue, Alizarin Brilliant Blue, Alizarin Brilliant Green, Dianol Green and Nigrosin. The following were not soluble throughout the *p*H range employed: Berlin Blue, Alizarin, Carmine, Congo Red and Ruthenium Red. The following faded or changed colour in alkaline solution: Cotton Blue, Nile Blue, Water Soluble Blue, Acid Fuschin, and many indicator dyes. The following gave an insufficiently intense colour: Orange *II*, Orange *RO*, Paramine Yellow *R*, and Paramine Fast Yellow 3 *G*. The following were fluorescent: Eosin, Eosin *A*, and others. Many of the above-mentioned dyes might be included in more than one category.

6. The dyes must not be fluorescent.

7. On mixing, the two dyes must both remain in solution and not mutually precipitate each other.

8. If possible, the dyes should be adsorbed only by hydrous alumina, and not to any great extent by hydrous silica, alumino-silicates, or ferric oxide. This is desirable, but not absolutely essential.

9. The two dyes should be adsorbed in approximately equal amounts at *p*H values equidistant from, but on opposite sides of, the isoelectric point. This again is not essential.

Preliminary blank tests were made with the dyes alone. Some of the dyes used were examined for impurities, and were salted out from solution by adding ammonium chloride. In no case, however, did purification appear to exert any appreciable effect on the amount of dye adsorbed.

The most successful combination of dyes found was Biebrich Scarlet (acidic) and Iodine Green (basic). When a mixture of these two dyes was added to a series of tubes, the tubes containing hydrous alumina on the acid side of the isoelectric point showed a green colouration, whilst on the alkaline side of the isoelectric point the supernatant liquid showed a red colouration. The position of the isoelectric point was indicated by a dull colouration due to the mixture of the two dyes. It was confirmed by testing some of the suspension with a quinhydrone electrode, and the colour change was always found to occur in the region of *p*H 6·5. Even when the *p*H values of the tubes deviated somewhat from their original values (as they were liable to do, since there was no buffering agent present), the tube containing the isoelectric colloid could easily be identified.

The next step was to attempt to demonstrate, by the use of the selected dyes, the existence of an isoelectric point at *p*H 6·5 in soils whose chemical analyses indicated that free hydrous alumina might be present.

A large number of soils of widely differing types were tested[1]. They were treated in exactly the same way as in the hydrous alumina experiments. A stock soil suspension was made, and the *p*H values of a series were then adjusted with hydrochloric acid and with dilute sodium hydroxide solutions. The dyes were added separately by the drop method until suitable concentrations were obtained. Great differences were exhibited by the various soils examined (*vide* Table of Results). Thus an Indian Laterite suspension showed a very definite colour change

[1] The soil samples were selected from a series collected by Prof. F. Hardy for examination in connection with other investigations into the characteristics of lateritic soils.

at the isoelectric point of hydrous alumina, whilst a Trinidad red soil produced a uniform colour throughout the series. The pH value at the transition point was always checked by means of a quinhydrone electrode, and always found to differ but little from pH 6·5. When the results were compared with the $SiO_2 : Al_2O_3 + Fe_2O_3$ ratio for the soils, it was found that only those soils with low ratios showed selective adsorption. It was possible to form a rough estimate of the numerical value of the ratio for any particular soil, or, at any rate, to gauge whether the ratio would be considerably less than unity, approximately unity, or considerably greater than unity. A series of five British Guiana bauxites and bauxitic clays provided interesting samples. Samples 3 and 9 showed marked positive reactions, whilst among the other three bauxitic samples it was possible to place one as having a much lower basic ratio than the other two.

TABLE OF RESULTS.

Relationship between basic ratio and dye test.

*Soil	Chemical analysis: Loss on Ignition	Al_2O_3	Fe_2O_3	SiO_2	$\frac{SiO_2}{(Al_2O_3+Fe_2O_3)}$ (Basic ratio)	Dye adsorption test
Bauxite 9	26·3	47·9	21·0	1·1	0·015	Very good
Bauxite 3	29·8	62·1	2·7	1·4	0·021	Very good
Indian laterite ...	12·4	21·7	31·5	34·0	0·639	Good
White bauxitic clay	22·8	46·6	1·7	26·8	0·554	Good
Cuba red	14·4	16·5	62·4	7·8	0·099	Fairly good
Java red	15·2	37·5	10·7	37·5	0·778	Fairly good
Dominica red ...	13·7	30·1	17·1	40·8	0·864	Fair
Hawaii red... ...	17·4	25·4	19·4	31·3	0·698	Fair
Barbados red ...	13·2	26·1	17·3	34·7	0·799	Fair
Pink bauxitic clay	14·4	38·0	5·0	42·3	0·983	Poor
Red bauxitic clay...	15·1	41·0	5·9	37·4	0·797	Poor
Anguilla red ...	14·4	27·7	28·1	30·6	0·548	Poor
Jamaica red *F*. ...	17·3	31·8	11·6	37·9	0·870	Poor
Jamaica red *B*. ...	15·9	29·2	13·2	41·0	0·966	Poor
Antigua grey ...	8·6	17·4	8·7	64·4	2·551	Poor
Trinidad red earth	7·0	31·6	8·8	54·5	1·348	Poor

* The soils are arranged in the order of their sensitivity to tne dye adsorption test.

With those clays or soils marked in the Table "Very Good" and "Good," a sharp change in colour from red to green was quickly obtained in the region of pH 6·5. The value of the test was enhanced by the rapidity with which lateritic clays settle from suspension. With some of the clays low down in the series, the tendency of the clay to remain in suspension somewhat vitiated the test. In these cases, it was impossible to judge the colour of the suspension liquid until it had become perfectly clear, the smallest trace of suspended matter coloured by the adsorbed dye im-

parting a colour to the liquid. The difficulty might be overcome by centrifuging. In soils marked "Fair," this effect tended to mask the colour. The clays towards the end of the series showed high adsorption of basic Iodine Green and poor adsorption of acidic Biebrich Scarlet, and the amount of each dye adsorbed became constant throughout the whole *p*H range. This result may readily be explained if the presence of preponderating amounts of free hydrous silica and alumino-silicates in these soils be postulated.

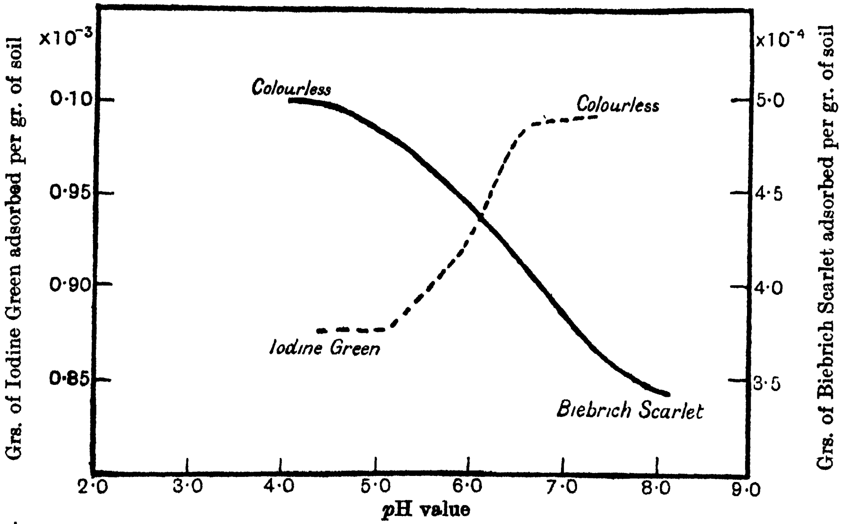


Fig. 1. Adsorption of dyes by Java clay.

For purposes of illustration, curves were drawn showing the relative amounts of the two dyes that were adsorbed at various *p*H values. One such curve is here reproduced as an example. The quantity of dye adsorbed was measured in each case by examining the supernatant liquid in a Duboscq colorimeter. Reaction values were determined by the quinhydrone electrode.

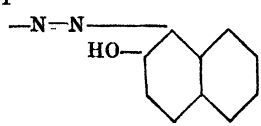
Discussion.

The foregoing experiments lay the foundation of a method for the rapid detection of free hydrous alumina in soils containing appreciable quantities of this substance, and thus for the identification of lateritic soils. The test, however, is not sufficiently precise for all purposes. More efficient dyes than those finally selected could undoubtedly be found. Biebrich Scarlet appears to be a fairly satisfactory acid dye, but basic Iodine Green fades considerably in alkaline solution, even in the dark,

and its colour changes are thereby accentuated. That the prominence of the Biebrich Scarlet in suspensions containing the two is not entirely due to the fading of the Iodine Green, but in some part to the removal of the latter by adsorption, is shown by the fact that, although between the isoelectric point *p*H 6·5 and *p*H 7·0 the green dye does not fade, practically all traces of it are removed by adsorption, and the red comes into prominence. A distinct difference may be noted, for instance, between the shade of colour in a tube at *p*H 6·5 and that in a tube at *p*H 6·8.

The possibility that hydrous ferric oxide may also act as an ampholyte must be considered. Artificially prepared colloidal hydrous ferric oxide behaved towards the two dyes in a manner very similar to that of artificially prepared hydrous alumina. Many lateritic soils contain a high percentage of iron oxide. Nevertheless, the probability of iron oxide occurring in a soil in a sufficiently hydrated form to interfere with the test, appears to be very small. For example, the Anguilla red soil and the Trinidad red soil, both containing relatively large amounts of iron oxide, show no colour change indicative of the presence of an ampholyte. Moreover, of the three British Guiana bauxitic clays, coloured respectively white, pink and red, the white clay, containing the lowest percentage of iron, showed the greatest and most definite colour change. This further indicates that the sensitivity of the test is not dependent upon the iron oxide content.

There appears to be no very definite correlation between the chemical constitution of dye-stuffs and their absorbability by soil colloids. It is interesting to note, however, that basic Iodine Green contains the very distinctive quaternary ammonium grouping $-\overset{\bullet}{N}(CH_3)_2Cl$, and that acidic Biebrich Scarlet, and also another similar red dye, Brilliant Crocein, contain the group



Two other dyes, Janus Yellow and Janus Red, each containing both these groups, are adsorbed only to a very small extent by hydrous alumina. They nevertheless both indicate the *p*H value of its isoelectric point, being absorbed mostly on the alkaline side. Certain soils adsorbed both these dyes in fairly large amount, but showed little change at the isoelectric point, presumably because they are adsorbed by components of the soil other than hydrous alumina.

A further observation demonstrating the applicability of the isoelectric theory in these studies is worthy of note. In the preparation of the tubes of various pH values before the addition of the dyes, it was possible to obtain with the more aluminous clays a series in which the clay in the tubes of extreme pH value would remain in suspension for a considerable period of time, whereas the suspended material at reactions progressively nearer the isoelectric point of hydrous alumina, settled more rapidly. In the immediate neighbourhood of the isoelectric point the clay settled from suspension almost spontaneously.

Acknowledgment. The writer wishes to acknowledge his indebtedness to Prof. F. Hardy to whom the original idea of this investigation is due, and whose advice and help throughout have proved most valuable. He is also indebted to Dr H. H. Hodgson, of the Huddersfield Technical College, for suggestions regarding the constitution of dye-stuffs, and for the gift of some samples.

SUMMARY.

1. A historical review of the dye adsorption method for the estimation of soil colloids is presented, and the method is criticised chiefly from the point of view of the isoelectric theory.

2. A procedure for the detection of hydrous alumina in soils is described, involving the demonstration of the isoelectric point of hydrous alumina by means of preferential dye adsorption in suspensions of various pH values.

3. Satisfactory results were obtained with a mixture of acidic Biebrich Scarlet and basic Iodine Green. The former is adsorbed by hydrous alumina only on the acid side of its isoelectric point, and the latter only on the alkaline side.

4. The characteristics of an ideal dye for use in studies such as those described are tabulated.

5. The applicability of the mixture of dye-stuffs finally selected is demonstrated for a series of soils of varying basic ratio, and including examples of lateritic soils and clays.

REFERENCES.

(1) ROHLAND. *Glasind* (1915), 26; *Chem. Abs.* **9**, 2701.
(2) GRAF ZU LEININGEN. *Koll. Z.* (1916), **19**, 165; *Chem. Abs.* **11**, 3076.
(3) HARDY. *J. Phys. Chem.* (1926), **30**, 254.
(4) WAY. *J. Roy. Agri. Soc.* (1850), **11**, 313–379; ASHLEY. *U.S. Geol. Survey Bull.* (1909), **388**.

(5) WARINGTON. *J. Chem. Soc.* (1868), **6**, 1.

(6) TSCHERMAK. *Zeit. Phys. Chem.* (1905), **53**, 349; *J. Chem. Soc. Abs.* **2**, **88**, 816.

(7) ASHLEY. *U.S. Geol. Survey Bull.* (1909), **388**.

(8) BEAUMONT. *Mem.* 21, *Cornell Univ. Agr. Expt. Sta.* (1919).

(9) WOOD and WOOLLER. *J. Soc. Dyers and Col.* (1925), **41**, 47; *J. Chem. Soc. Abs.* **2**, 128, 285.

(10) BANCROFT. *J. Phys. Chem.* (1914), **18**, 118; *J. Chem. Soc. Abs.* **2**, 106, 250.

(11) WILKINSON and HOFF. *J. Phys. Chem.* (1925), **29**, 808.

(12) TESTONI. *Ann. Chim. Appl.* (1926), **16**, 45; *Chem. Abs.* **20**, 1931.

(13) BECHOLD. *Koll. Z.* (1918), **23**, 35; *J. Chem. Soc. Abs.* **1**, 114, 516.

(14) SJOLLEMA. *J. Landw.* (1905), **53**, 67; *J. Chem. Soc. Abs.* **2**, 88, 195.

(15) ROHLAND. *Z. Anorg. Chem.* (1914), **89**, 164; *J. Chem. Soc. Abs.* **2**, 108, 424 *Koll. Z.* **15**, 180; *J. Chem. Soc. Abs.* **2**, 108, 234.

(16) HANLEY. *J. Agric. Sci.* (1914), **6**, 58.

(17) GILE, MIDDLETON, ROBINSON, FRY and ANDERSON. *U.S. Dept. Agric.* (1924), *Bull.* 1193.

(*Received February* 13*th*, 1928.)

FACTORS AFFECTING THE IRON AND MANGANESE CONTENT OF PLANTS WITH SPECIAL REFERENCE TO HERBAGE CAUSING "PINING" AND "BUSH-SICKNESS."

BY W. GODDEN AND R. E. R. GRIMMETT.

(From the Rowett Research Institute, Aberdeen, and the Department of Agriculture, New Zealand.)

IN the account of "Pining" in sheep given by McGowan (1) there are so many points of similarity, both in the symptoms and in the general environmental conditions under which the disease is developed, with the disease known in New Zealand as "Bush-sickness," as to suggest that these two diseases may be of a similar nature.

The onset of bush-sickness in sheep or cattle has been shown by Aston (2) to be due to the stock grazing upon pasture which has an abnormally low iron content, although noted in other respects for its fattening qualities. The extreme anaemia, which results, is cured by administering suitable iron compounds, such as iron ammonium citrate, or by removal of the animals to pastures rich in iron. The animals can then be returned to the former grazing, and will thrive for a considerable period before again needing to be changed.

Following on the observations of McGowan on pining (*loc. cit.*), an investigation, the details of which have not as yet been published, has been in progress at this Institute into the relative mineral contents of pasture from pining and non-pining areas, and in general the results show that the iron-content is lower in the pining than in the non-pining herbage. Qualitative observations suggest also some difference in the manganese content. One case has been reported to us where a shepherd obtained markedly beneficial results by administering iron ammonium citrate to sheep suffering from pining. In view of the above facts it was decided to take advantage of a short visit to this country by one of us (R. E. R. G.), familiar with the conditions under which "bush-sickness" is prevalent in New Zealand, to study some of the factors affecting the assimilation of iron and manganese by the plant.

Aston and Grimmett (3) have shown that "bush-sickness" and iron deficiency in pastures in New Zealand are apparently associated with certain definite physiographic and soil conditions, such as a sandy soil

with less than 5 per cent. of clay, resting on a pervious sub-stratum, elevated considerably above the permanent water-table, in a region usually of fairly extensive, level or undulating hill top, where the annual rainfall is high. Under such conditions, favourable to soil aeration and leaching, the total amount of soluble iron in the soil at any one time is small, and it is only the pasture growing on the lower seepage areas which is rich in iron. The above description applies equally to typical pining country (cf. McGowan, *loc. cit.*).

RECENT INVESTIGATION.

The work outlined briefly below, while admittedly preliminary in character owing to the short space of time available due to a late start, has brought out one or two points of interest.

Pot experiments were laid down, some with "pining" soil and some with sand. The "pining" soil, from a typical area, showed, on analysis (cf. Table I), a very similar mechanical composition to that of bush-sick soils as recorded by Aston (4). Both soils are sandy silts with a clay content of less than 3 per cent. The pining soil is richer in nitrogen and both total and available phosphorus and potash than the bush-sick soil, but poorer in calcium. It has a high lime requirement (0·52 per cent. $CaCO_3$).

Table I. *Analysis of "Pining" and "Bush-sick" Soils.*

	Mechanical analysis: Pining soil	Bush-sick soils (Aston) (S/181)	Bush-sick soils (Aston) (R/976)
	%	%	%
Fine gravel	15·75	1·3	19·8
Coarse sand	16·74	30·5	38·8
Fine sand	15·82	27·4	14·9
Silt	18·16	18·6	8·4
Fine silt	11·40	8·5	5·3
Clay	1·10	2·3	0·8
Moisture	8·94	1·6	1·0
Loss on ignition	11·16	9·8	9·1
Matter soluble in dilute HCl	0·96	—	—
	100·03	100·0	98·1

Chemical analysis (on soil dried at 100°)		Pining soil	Bush-sick soils (S/181)	Bush-sick soils (R/976)
		%	%	%
Nitrogen		0·45	0·222	0·255
P_2O_5	Total	0·14	0·01	0·03
	Avail.	0·023	0·004	0·002
K_2O	Total	0·45	0·07	0·08
	Avail.	0·024	0·015	0·019
CaO	Total	0·061	0·15	0·47
MgO		0·45	—	0·20
Fe_2O_3	Total	2·60	—	—
	(Cit. sol.)	0·052	0·103	0·04
Mn_2O_3	Total	0·19	—	—
	(Cit. sol.)	0·043	—	—

Lime reqt. 0·52 % $CaCO_3$

The pot experiments were designed to test the effects of (*a*) lack of drainage, (*b*) the application of organic matter, (*c*) the application of iron in various combinations, (*d*) the application of sulphur either in the free state or as ferrous sulphate, (*e*) the application of lime on the iron and manganese content of the crops. These factors were selected in view of the results obtained in the bush-sickness investigation.

Five series of pots were set up, in three of which sand was the medium, in the fourth pining soil, and in the fifth local arable soil was used. The sand was of granitic origin from a local pit. Ordinary 11-in. flower pots were used and these were well coated inside with high M.P. paraffin wax prior to filling in order to prevent any iron contamination from the pot. Where drainage was not wanted, the holes at the base were stopped up with corks soaked in wax. The arrangement of the pots in four of the series is shown in Tables II and III, where the analytical data for the crops are given. The results for the other series, where 5 per cent. of humus was incorporated with the sand, are omitted owing to lack of growth. The sand pots were each inoculated with two ounces of pining soil.

Table II.

Series A. Each pot contained 24 lb. sand* over 1 lb. of granite chips.

	Subseries (*a*) Drained				Subseries (*b*) Undrained			
		Percentages on dry matter				Percentages on dry matter		
Treatment and crop	Crop wt. (dry) gm.	Ash %	Fe %	Mn %	Crop wt. (dry) gm.	Ash %	Fe %	Mn %
1. Control:								
Oats	0·573	17·32	0·025	0·011	0·808	17·27	0·019	0·082
Mustard	0·504	20·30	0·028	0·011	0·187	19·85	0·027	0·033
2. Ferric oxide 2 cwt. per acre:								
Oats	0·729	18·52	0·019	0·009	0·709	17·37	0·020	0·072
Mustard	0·290	19·22	0·027	0·007	0·363	18·37	0·021	0·029
3. Ferric oxide 2 cwt. S. 1 cwt. per acre:								
Oats	0·601	21·53	0·017	0·027	0·725	18·28	0·025	0·091
Mustard	0·556	22·64	0·032	0·022	0·066	18·07	0·057	0·069
4. Ferrous sulphate 1 cwt. per acre:								
Oats	0·706	16·20	0·020	0·019	0·749	18·78	0·023	0·092
Mustard	0·252	18·92	0·026	0·010	0·350	18·34	0·038	0·032
5. Ferrous phosphate 1 cwt. per acre:								
Oats	0·676	18·14	0·021	0·012	0·628	18·15	0·023	0·078
Mustard	0·418	21·57	0·028	0·007	0·211	18·34	0·032	0·034
6. 5 % of K "ball clay" 1 cwt. of ferrous sulphate per acre:								
Oats	0·483	15·86	0·020	0·029	—	—	—	—
Mustard	0·918	21·07	0·015	0·007	—	—	—	—

* The sand contained 1·14 % Fe_2O_3 and 0·019 % Mn_2O_3 soluble in concentrated HCl and only a trace soluble in dilute citric acid.

Each pot was planted on August 14 with four oat seedlings, four pairs of mustard seeds, three red clover and three cocksfoot seedlings, but only

the oats and mustard grew. The pots were out of doors until September 12 and were then taken into a room in the building. They were watered from time to time as required with distilled water, all the drained pots being treated alike in this respect. On October 24, growth having ceased, the plants were cut half an inch above the soil level, the oats and mustard being kept separate. The crop from each pot was weighed green, again after drying at 100°, and on the dry material determinations were made of total ash, iron and manganese.

Method of Analysis. For the determination of iron and manganese, the whole crop was ashed at a temperature just below a dull red heat. The ash was evaporated with 0·5 c.c. of concentrated hydrochloric acid and then heated with 2 c.c. of concentrated sulphuric acid till white fumes appeared. The residue when cold was diluted with 20 c.c. of water, filtered, washed with 10 per cent. sulphuric acid and the filtrate and washings made up to 50 c.c. with this dilute acid. Iron was determined colorimetrically with ammonium thiocyanate on 5 or 10 c.c. of this solution. Manganese was determined on suitable aliquot portions colorimetrically, after oxidation with sodium periodate, as described by Willard and Greathouse (5). The analytical data are recorded in Tables II and III.

Table III.

Series D. Each pot contained 24 lb. of pining soil above 1 lb. "pining" stones. The analytical data are for the oats only.

Treatment	Crop weight (dry) gm.	Percentages on dry matter: Ash %	Fe %	Mn %
1. Control—Undrained	0·100	13·84	0·025	0·280
2. Control—Drained	0·188	15·97	0·017	0·181
3. Ferrous sulphate 1 cwt. per acre	0·175	16·02	0·022	0·169
4. Basic slag 2½ cwt. per acre	0·390	18·95	0·018	0·213
5. Precipitated chalk 5·2 tons per acre	0·950	20·11	0·019	0·051
6. Sulphur 2 cwt. per acre	0·191	15·69	0·020	0·170
7. Superphosphate 2½ cwt. per acre	0·372	19·47	0·021	0·195

Series E. Each pot contained 24 lb. local arable soil* above 1 lb. granite chips.

Treatment	Crop weight (dry) gm.	Ash %	Fe %	Mn %
1. Control:				
Oats	0·224	17·87	0·020	0·013
Mustard	0·529	20·00	0·043	0·006
2. Precipitated chalk 3·1 tons per acre:				
Oats	0·194	16·93	0·032	0·007
Mustard	0·764	22·13	0·038	0·005

* This soil gave: clay 1·25 %; loss on ignition 11·5 %; total Fe_2O_3 3·05 %; Mn_3O_4 0·11 %, and had a lime requirement equal to 0·31 % $CaCO_3$.

DISCUSSION OF RESULTS.

It will be noted that, in most cases, the percentage of iron is higher in the mustard than in the oats, while the reverse is true for manganese. In the sand cultures the manurial treatment appears to have had but little effect during the short period of growth, except that sulphur, either free or as sulphate, has slightly raised the percentage of manganese in the crop.

Drainage conditions, while not as yet influencing the iron, have had a marked effect on the manganese content of the plant. Lack of drainage has increased the manganese content of the oats, on the average, about six times and rather less in the mustard (cf. Table II). The water-logged and mildly reducing conditions have apparently had more effect on the manganese than the iron, in rendering it available. This might be expected as the higher oxides of manganese are known to be more readily reduced than those of iron.

The addition of 5 per cent. of clay (pot 6, Table II) had no definite effect on either the manganese or iron content of the crop.

The most interesting comparisons are obtained in the series grown on the pining soil (series D, Table III). The mustard seedlings failed to grow, possibly owing to their higher requirement for iron, and in the limed pot became markedly chlorotic prior to dying off. The iron content of the oats is fairly uniform throughout the series of pots. The manganese is, however, again much higher in the undrained pot, but, on the other hand, the application of chalk has definitely depressed it. Other manurial treatment appears to have been without effect on either the iron or the manganese.

It should be noted that, while the percentage of iron in the crop from this series is approximately the same as that in the crop grown on sand, the percentage of manganese is more than ten times as high in series "D" as in series "A" (*a*). This high manganese content was reflected during the ashing of the plant material, which burnt with almost explosive violence.

In the case of the plants grown in the local soil, the only point of interest is the difference in the iron-manganese ratio. In contrast with the crops grown on the pining soil, both the oats and mustard grown on the local soil have a higher percentage of iron than manganese. The percentages of iron and manganese in the sand, pining soil and local soil, taken in conjunction with the percentages of these constituents in the

oats and mustard grown on these media, suggest that manganese is more easily taken up from the soil by the plant than is iron.

The above experiments are admittedly tentative and cover too short a growing period. It is hoped, however, to continue this work and obtain results for mature plants. In the meantime it appears that on a given culture medium, lack of drainage is the most potent factor in increasing the manganese content and the manganese-iron ratio of the crop. Liming, on the other hand, tends to decrease both of these.

REFERENCES.

(1) McGowan, J. P. and Smith, W. G. (1922). *Scottish Journ. Agric.* **5**, 274.
(2) Aston, B. C. (1924). *N. Z. Journ. Agric.* **28**, 215, 301, 381; **29**, 14, 84.
(3) —— (1926). *N. Z. Journ. Agric.* **32**, 365.
—— (1927). *N. Z. Journ. Agric.* **35**, 96.
Grimmett, R. E. R. (1927). *N. Z. Journ. Agric.* **34**, 289.
(4) Aston, B. C. (1924). *N. Z. Journ. Agric.* **29**, 369.
—— (1925). *N. Z. Journ. Agric.* **30**, 1.
(5) Willard, H. H. and Greathouse, L. H. (1917). *J. Amer. Chem. Soc.* **39**, 2366.

(*Received February* 1*st*, 1928.)

STUDIES IN MINERAL METABOLISM. III.*

BREEDING OF CATTLE ON PHOSPHORUS DEFICIENT PASTURE.

By A. THEILER, H. H. GREEN and P. J. du TOIT.
(*Division of Veterinary Services, Onderstepoort, Pretoria.*)

In a preceding article, "Minimum Mineral Requirements in Cattle" (1), mention was made of work in progress in regard to the practical possibilities of grading up scrub herds on phosphorus deficient veld, by combining introduction of pure-bred bulls with rationing of the herd upon mineral supplement.

In the earlier article, "Phosphorus in the Live-Stock Industry" (2), the question of mortality from various causes associated with mineral deficiency was discussed, and experiments foreshadowed concerning the effect of aphosphorosis upon the fertility of cattle. The breeding experiments were commenced in 1925, and planned to extend over a period of at least twelve years, but the preliminary results during the first two years have been so striking that they may be profitably indicated now, leaving detailed protocols to follow when the main line of work is further advanced.

The experiment consisted in culling the original scrub herd (on the farm Armoedsvlakte, Vryburg, Cape Province) used for the work recorded in "Phosphorus in the Live-Stock Industry," and dividing the residual cows into four batches of fifty according to conjectural suitability for mating with the pure-bred bulls about to be introduced. The bulls selected were Afrikander, Sussex, Friesland, and Red Poll; beef type, milk type, and dual purpose type, being so represented. Each batch of fifty was again divided into two, one receiving a supplement of bone meal to rectify the phosphorus deficiency of the natural pasture, the other remaining as "controls" confined to veld grazing.

* This article is to be taken as the third in a series of which "Phosphorus in the Live-Stock Industry" is to be regarded as the first, and "Minimum Mineral Requirements in Cattle" as the second. Later articles may be associated with any authorship and the object of arranging in series is partly to indicate that the economic significance of some of the publications may only be evident when taken in conjunction with the rest, partly to allow of provisional progress reports on long-continued experiments, and partly to indicate that all work is under the general control of the Director of Veterinary Services of the Union of South Africa. The present paper represents work commenced before the retirement of Sir Arnold Theiler.

As the experiment proceeds, it is the intention to supply a mineral supplement to the majority of the heifer calves of successive generations, and to utilise a certain proportion as controls in order to ascertain not only the extent to which pure bred types can be built up on ranching veld worth only a few shillings per acre, but also to ascertain the extent to which cattle bred towards type tend to revert to scrub, as a direct result of aphosphorosis.

Side branches of the main experiment, such as influence of mineral supplement upon configuration of beef types and upon lactation in milk types, suitability of the area concerned for different breeds, and costs of beef production on land unsuitable for cultivation of any kind, need not be detailed at this stage. Now that the first-cross calves have passed their first year of life, however, the following outline of outstanding provisional results may be communicated:

(1) *Mortality Incidence.* Ignoring deaths from accident or infectious disease, 27 cows (out of 200) died from "Lamsiekte," *i.e. botulism* of bovines; 7 died from plant poisoning; and 5 from "poverty" (cachexia complicated by incipient styfsiekte). Of the 27 which died from Lamsiekte, 25 were "controls" and only 2 were from the batches receiving the small ration of bone meal. Since all visible carcase debris of larger animals was systematically removed by periodic search, the source of toxic carrion (ingestion of which produces the disease) was generally small wild life; birds, hares, meerkats, tortoises, lizards. The salvation of the cattle receiving the mineral supplement was therefore due to obviation of depraved appetite (osteophagia). Of the 7 cows which died from plant poisoning, 5 were controls; the suggestion being that depraved appetite reduces discrimination in selective grazing. Of the 5 which died from "poverty," all were controls; no deaths from malnutrition occurring amongst the cattle receiving mineral supplement.

Of the control cattle on the farm in 1925, only 47 per cent. remained alive in 1927. The cows limited to the natural grazing are therefore *dying out*, and if the same mortality incidence continues one branch of the experimental programme will disappear. The farm will then have been shown to be *worthless for cattle rearing without mineral supplement.*

(2) *Fertility.* Of the cows receiving the bone meal ration, 80 per cent. calved normally—a fair calf crop when the varying age and character of the herd is taken into consideration. Of the control cows only 51 per cent. (36 out of 70) calved.

Observations during the first year were not sufficiently detailed to enable a physiological explanation of these data to be offered, but the

broad fact, as it interests the farmer, stands out clear. The "calf crop" is increased by bone meal feeding. As the experiment proceeds and the history of the heifer calves is followed from birth onwards, it will become possible to go more deeply into the problem of fertility as influenced by aphosphorosis.

(3) *Character of Calves.* Of the calves born to pure bred sires out of random mothers, 80 per cent. show a tendency, in external configuration, to the breed of the father. Those calves from mothers supplied with a bone meal ration, and themselves receiving such supplement from weaning onwards, show an enormous superiority of development over those calves born of control mothers and themselves receiving no mineral supplement after weaning. The best of the batch of first-cross calves weighed 700 lbs. at the age of 15 months; nearly twice the average weight of the calves born of control mothers at about the same time, and a truly astonishing figure for the arid veld of Armoedsvlakte, the carrying capacity or grazing value of which is usually reckoned at about 20 acres per beast.

Our earlier data (*loc. cit.* (2), Fig. 9) leave no room to doubt that differences between the two batches of first-cross beef breed calves will be further magnified as they grow to full maturity.

SUMMARY.

On the arid, sparse, phosphorus deficient pasture of the Vryburg district of the Cape Province, grading up of scrub cattle, by combining the introduction of pure bred bulls with the feeding of bone meal to the cows, is attended with great success so far as shown by the first crossing. Remarkable differences in favour of the mineral supplement are shown, in respect to reduced mortality incidence, increased fertility of cows, and superior development of calves.

REFERENCES.

(1) THEILER, A., GREEN, H. H., and DU TOIT, P. J. (July, 1927). *J. Agric. Sci.* **17**, 291.

(2) —— —— —— (May, 1924). Phosphorus in the Live-Stock Industry. Journal Department of Agriculture, Union of South Africa.

(*Received February 14th*, 1928.)

STUDIES IN MINERAL METABOLISM. IV.

DETERMINATION OF PHOSPHORUS COMPOUNDS IN BLOOD BY DRY COMBUSTION.

By H. H. GREEN.

(*Division of Veterinary Services, Onderstepoort, Pretoria.*)

In the customary methods for determination of the phosphorus partition of blood, wet combustion methods for destruction of organic matter, followed by the use of the colour reaction between phosphate and ammonium molybdate in presence of sulphuric acid and a reducing agent, are almost universally adopted. In the various modifications and amplifications of the Bell and Doisy method (1920), as for instance by Randles and Knudson (1922), Briggs (1924), and Stanford and Wheatley (1925), quinol is used as reducing agent.

In this Laboratory, dry combustion methods, followed by a modification of the ceruleo-molybdate method of Deniges (1920), had been successfully used in 1923 for micro-determination of phosphorus in grass leaves, and later adapted by Lonstein (1926) for rapid determination of total and citric-soluble phosphorus in soils. In the Deniges method, only applicable in absence of interfering organic matter, stannous chloride is used as reducing agent, giving a more intense colour which develops very rapidly.

In subsequent work on blood, the dry combustion methods, combined with the Deniges procedure, were also tried, and after testing against the wet methods were found more rapid and convenient for routine use. They can also be brought within the scope of a portable outfit and so used in a "field laboratory" in which paraffin or alcohol burners take the place of gas, rendering wet combustion awkward.

As tested by G. J. R. Krige and A. I. Malan, in this Laboratory, intelligent manipulation enables six phosphorus partitions (24 determinations) to be completed in an uninterrupted eight-hour day; including drawing of blood samples and handing in of final results.

Since the purpose of this note is merely to draw attention to the methods, familiarity with the procedure of Stanford and Wheatley (1925), and with the usual precautions necessary in micro-technique, may be presumed, and the processes given as briefly as possible.

REAGENTS REQUIRED.

(1) Twenty per cent. sodium citrate solution as anticoagulant. 1 c.c. to 2 c.c. of this per 100 c.c. of blood is sufficient, and the small correction for dilution can therefore be made at sight, on the final results, or even ignored for most purposes.

(2) Twenty per cent. trichloracetic acid. The strength need only be approximate, but the solution should be freshly prepared at intervals of a few days.

(3) Ten per cent. sulphuric acid and strong ammonia, tested for freedom from ceruleo-molybdate colour reaction.

(4) One per cent. quinol solution, freshly prepared at intervals of about a fortnight.

(5) Twenty per cent. sodium sulphite solution.

(6) Mixture of absolute alcohol 3 volumes, and pure ether 1 volume.

(7) One per cent. stannous chloride, *freshly prepared* on the day of use, rapidly obtained by heating approximately 0·1 gm. pure tinfoil with 2 c.c. of concentrated hydrochloric acid in a test-tube with a drop of 5 per cent. copper sulphate as catalyst, diluting to approximately 10 c.c. with cold water, and filtering.

(8) Ten per cent. calcium acetate solution, phosphorus free.

(9) Reagent A, for inorganic phosphorus determination only, using quinol as reducing agent. 25 gm. ammonium molybdate dissolved in 300 c.c. of water, and mixed with 75 c.c. of concentrated sulphuric acid diluted with 125 c.c. of water. The usual Briggs reagent.

(10) Reagent B, for total phosphorus, total acid-soluble phosphorus, and lipoid phosphorus. 10 gm. ammonium molybdate dissolved in 100 c.c. of water, and mixed with 150 c.c. of sulphuric acid diluted with 150 c.c. of water. The usual Deniges reagent.

(11) Standard phosphate solutions. These may readily be prepared by direct weighing of Merck's G.R. microcosmic salt, dehydrated in a desiccator for a few days. A stock solution of any desired strength is made up and diluted as required, to give standard solutions for use, corresponding to 1 mg. P or 2 mg. P_2O_5 per 100 c.c., according to the method adopted in expressing results.

Quantities of Blood used. The quantities of blood and blood filtrates used depend upon the amount of the various phosphorus fractions expected, and upon the need for economy in blood sampling. The following quantities are those used for bovine blood, obtainable in unlimited quantities from the jugular vein.

Total Phosphorus. Into a 10 c.c. calibrated measuring cylinder containing a few c.c. of water, pipette 2 c.c. of citrated blood, add water up to mark, and invert to lake and mix. Pipette 2 c.c. of this laked blood, equivalent to 0·4 c.c. of whole blood, into a small porcelain basin containing 2 drops of 10 per cent. calcium acetate solution, evaporate to dryness on the steam bath, and combust the residue over a free flame (or in an electric muffle). Complete ashing is attained in about *three minutes.* To the ash add 10 c.c. of 10 per cent. sulphuric acid, extract on the steam bath for a few minutes and filter quantitatively into a 100 c.c. measuring cylinder, washing up to about 60 c.c. with cold water. Alkalinise faintly with strong ammonia, using phenolphthalein as indicator, bring to approximate neutrality with a few drops of 10 per cent. sulphuric acid, add 2 c.c. of reagent B, and bring up to the 100 c.c. mark with water. Prepare the standard for comparison, at the same time, by pipetting 10 c.c. of phosphate solution, equivalent to 0·1 mg. P (or 0·05 mg. P) into a 100 c.c. cylinder, adding 10 c.c. of 10 per cent. sulphuric acid, neutralising with ammonia, acidifying, adding reagent B, and diluting to 100 c.c. with water. To both standard and unknown add 10 drops of fresh stannous chloride, allow 10 minutes for full development of colour, and compare in a colorimeter (*e.g.* Bausch and Lomb modified Duboscq), setting the standard at 30, and reading the unknown between the limits 25 to 40.

Lipoid Phosphorus. The method is simply the application of the procedure given above to the method of Rangles and Knudson (1922) for lipin phosphorus.

Pipette 4 c.c. of citrated blood into a 100 c.c. measuring flask containing about 80 c.c. of alcohol-ether mixture, shake, and warm to boiling on the steam bath. Cool, make up to mark with alcohol-ether and filter. Pipette 20 c.c. of filtrate into a porcelain basin containing 2 drops of calcium acetate solution, evaporate, and proceed as for total phosphorus.

Total Acid-Soluble Phosphorus. Pipette 30 c.c. of water into a small Erlenmeyer flask, run in 10 c.c. of citrated blood, and at once add 10 c.c. of 20 per cent. trichloracetic acid. Immediate addition avoids the hydrolysis of organic phosphorus which occurs when laked blood is allowed to stand (Martland and Robison, 1924). Close with the thumb and shake *vigorously* to ensure complete precipitation of the proteins, and so avoid the difficulty noted by Robinson and Huffman (1926) in obtaining a clear filtrate. Allow to stand about half an hour and filter. Take 5 c.c. of filtrate, equivalent to 1 c.c. of whole blood (or less if much organic ester phosphorus is expected), and proceed as for total phosphorus.

Inorganic Phosphorus. Since stannous chloride reduction is not reliable in presence of organic ester phosphorus, the method is simply a minor modification of the Bell and Doisy, or Briggs procedure.

Pipette 10 c.c. of the trichloracetic filtrate above, equivalent to 2 c.c. of blood, into a 25 c.c. measuring cylinder, bring to faint pink to phenolphthalein with ammonia, back to colourless with a drop of 10 per cent. sulphuric acid, and add successively 1·5 c.c. each, of reagent A, quinol, and sodium sulphite. Prepare the standard simultaneously by adding 2 c.c. of the trichloracetic acid solution to 10 c.c. standard phosphate solution (1 mg. P), neutralising and adding reagents precisely as with the unknown. Make both up to the same volume, 17·5 c.c., allow to stand 30 minutes for full colour development, and compare in the colorimeter.

Organic Acid-Soluble Phosphorus. Obtained as difference between total acid-soluble and inorganic.

Remarks. Apart from the concordance of results obtained by comparison with the conventional methods (Stanford and Wheatley) in the hands of four independent workers, accuracy is evidenced by the results of numerous analyses of blood of adult healthy bovines, in which the sum of the lipoid phosphorus and total acid-soluble phosphorus is equal to the figure for total phosphorus.

Summary.

Determination of the phosphorus partition in blood is described, combining dry combustion with the ceruleo-molybdate procedure of Deniges. Advantages in speed and convenience are claimed over the conventional Briggs methods.

REFERENCES.

(1) Bell, R. D. and Doisy, E. A. (1920). *J. Biol. Chem.* **44**, 55.
(2) Randles, F. S. and Knudson, A. (1922). *J. Biol. Chem.* **53**, 53.
(3) Briggs, A. P. (1924). *J. Biol. Chem.* **59**, 255.
(4) Stanford, R. V. and Wheatley, A. H. M. (1925). *Biochem. J.* **19**, 697.
(5) Deniges (1920). *Compt. rend. Soc. Biol.* **84**, 875.
(6) Lonstein, I. (1926). *S. Afric. J. Sci.* **23**, 188.
(7) Martland, M. and Robison, R. (1924). *Biochem. J.* **18**, 765.
(8) Robinson, C. S. and Huffman, C. F. (1926). *J. Biol. Chem.* **67**, 257.

(*Received February* 14*th*, 1928.)

STUDIES IN MINERAL METABOLISM. V.

COMPOSITION OF BOVINE BLOOD ON PHOSPHORUS DEFICIENT PASTURE.

By A. I. MALAN*, H. H. GREEN, and P. J. du TOIT.
(*Division of Veterinary Services, Onderstepoort, Pretoria.*)

In the article "Minimum Mineral Requirements in Cattle" (Theiler, Green, and du Toit, 1927), it was shown that in experimentally produced aphosphorosis, ultimately leading to "Styfsiekte" (stiff-sickness), there was a marked reduction in the inorganic phosphorus fraction of the blood.

In Article III of this same series, "Breeding of Cattle on Phosphorus Deficient Pasture" (Theiler, Green, and du Toit, 1928), preliminary data are given concerning an experiment, on the farm Armoedsvlakte, Vryburg, Cape Province, upon the grading up of scrub cattle by combining introduction of pure bred bulls with rationing of the herd upon mineral supplement.

The present article offers provisional data from this experiment, which demonstrate quite conclusively that under natural ranching conditions phosphorus deficiency of the pasture is directly reflected in the blood of cattle grazing over it, whether such deficiency is sufficiently acute to lead to clinically recognisable disease or not.

An easy method is thus provided for differential diagnosis of malnutrition due to aphosphorosis, and for obtaining information from the animal itself concerning "pasture eaten."

In obtaining the following data, attention was chiefly confined to inorganic phosphorus, but a sufficient number of complete determinations of "phosphorus partition" was undertaken to test the supposition that striking differences would be found mainly in that fraction. The methods used were those recorded in Article IV of this series (Green, 1928). A few determinations of calcium (oxalate permanganate micro-titration) are also included.

Table I offers comparison between dry cows, lactating cows confined to veld grazing, and similar cows systematically dosed with 3 ounces of bone meal per head per day (excluding Sundays).

* Webb Research Scholar, from University of Stellenbosch, attached to Biochemical Laboratories, Onderstepoort. Wholly responsible for analytical data.

Table I. *Analysis of Whole Blood.*

Inorganic elements in milligrams per 100 c.c.

COWS WITH CALVES AT FOOT.

Ration of 3 oz. bone meal per day.

No. of animal	1326	1252	1424	1427	1320	1250	1260	1410	1268	1479	1481	1494	1505	1488
Age of animal (years)	6	10	10	10	6	10	10	10	10	4	4	4	3	4
Period of lactation (months)	6	7	7	7	7	5	7	5	7	6	5	7	5	7
Total P	13·8	—	13·2	—	—	14·5	—	—	—	—	—	—	—	—
Lipoid P	7·9	—	8·0	—	—	7·5	—	—	—	—	—	—	—	—
Inorganic P	3·7	4·3	2·6	2·8	3·5	3·3	3·2	2·6	3·1	4·3	2·9	3·4	2·8	2·5
Organic acid-soluble P	2·3	—	2·6	—	—	3·5	—	—	—	—	—	—	—	—
Ca	—	—	9·9	10·1	13·4	9·7	11·9	10·3	11·6	10·3	—	9·3	9·3	—

CONTROL COWS WITH CALVES AT FOOT. VELD GRAZING ONLY.

No. of animal	1296	1620	1251	1409	1392	1246	1580	1502	1499	1572	1575	1487
Age of animal (years)	7	10	10	10	10	10	3	3	4	3	3	4
Period of lactation (months)	7	7	7	7	7	5	6	7	7	6	7	7
Total P	10·6	—	9·1	8·6	13·1	—	9·0	—	—	—	—	—
Lipoid P	6·8	—	5·9	5·4	6·5	—	5·8	—	—	—	—	—
Inorganic P	1·0	1·0	1·6	1·2	3·6	1·0	1·9	1·3	1·4	1·2	1·0	2·6
Organic acid-soluble P	2·6	—	1·6	1·9	3·0	—	1·3	—	—	—	—	—
Ca	—	11·0	11·2	11·8	11·1	—	—	10·7	12·8	14·2	11·3	—

DRY COWS.

	Bone meal fed animals							Control animals							
No. of animal	1261	1437	1416	1596	1434	1397	469	1236	1406	1234	1571	1308	1269	582	1622
Age of animal (years)	10	9	11	3	9	4	5	10	10	10	3	7	10	5	6
Total P	—	—	—	—	14·0	14·4	—	10·5	10·4	—	—	—	—	—	—
Lipoid P	—	—	—	—	8·0	7·9	—	4·6	4·6	—	—	—	—	—	—
Inorganic P	3·3	3·8	3·4	4·2	3·0	4·3	4·2	1·7	1·6	1·5	2·4	1·3	1·0	1·6	1·9
Organic acid-soluble P	—	—	—	—	3·0	2·1	—	4·2	4·2	—	—	—	—	—	—
Ca	10·3	10·6	10·6	13·0	—	—	—	11·1	11·8	12·6	11·7	—	—	—	—

Surveying the data, it is at once evident that the outstanding characteristic of the blood of all the control animals, *i.e.* those subsisting exclusively on the phosphorus deficient pasture, is the low *inorganic phosphorus* fraction. In noting the data, it should be explained that many of the figures recorded in the tables as 1 mg. should in reality be recorded as "less than 1 mg.," since colorimetric matching became uncertain below this limit.

The average for the lactating cows receiving bone meal is 3·1 mg. per 100 c.c. of whole blood, and for those receiving none is only 1·5 mg. For the dry cows the corresponding averages are 3·7 mg. and 1·6 mg. The inorganic P fraction is thus twice as high for the bone meal lot as for the controls, although even with the former the figure is definitely below the average for cattle on abundant phosphorus intake (*circa* 5 mg.). In general, 3 ounces of bone meal is not sufficient for lactating cows on this pasture (*loc. cit.* (4), p. 16).

It is noteworthy that with the exception of No. 1392 the figures do not overlap, and the controls are readily differentiated from those receiving phosphorus supplement. The reason for the relatively high figure for control 1392 is probably the fact that until the year preceding calving it had been rationed on bone meal, and that its skeletal reserves still sufficed to prevent manifestation of aphosphorosis.

In regard to the lipoid P fraction, the present data are too scanty for purposes of generalisation, although No. 1236 and No. 1406 certainly suggest that in dry cows suffering from phosphorus deficiency this fraction may also be abnormally low. The relatively high organic acid-soluble P of the same two animals may be noted in passing; but without comment in the meantime.

The total phosphorus is reduced in the blood of the control animals, mainly as a result of reduction in the inorganic fraction.

In regard to calcium little comment is required, beyond the statement that it is not low. The range 9·3 mg. to 12·8 mg. may be provisionally accepted as normal. The high figure 14·2 mg. for No. 1572 may possibly be erroneous (single analysis), but is also explainable on grounds which will be discussed in subsequent studies.

In regard to the general condition of the animals, it should be recorded that, with very few exceptions, the animals receiving bone meal could be readily sorted out from the controls at sight, on their markedly superior condition and higher weight; a point already discussed in the illustrated article "Phosphorus in the Live-Stock Industry" (Theiler, Green, and du Toit, 1924). As would be expected, the difference in condition was

more manifest in the lactating than in the dry cows. In the case of control dry cow No. 1571, indeed, the general well-nourished appearance would not have suggested mineral deficiency, although the figure for inorganic P of the blood does suggest that its development would have been enhanced by bone meal feeding.

Of the cows shown in Table I, Nos. 1296, 1251, 1246, 1502, 1499 and 1575 (all lactating) were regarded as showing incipient *Styfsiekte*[1] (*loc. cit.* (1)), but the symptoms were not so marked as to warrant a definite clinical diagnosis independently of the knowledge that the pasture was deficient in phosphorus. In the light of the blood analysis, however, no doubts were entertained.

Nos. 1620, 1409, 1392, 1580, 1572 and 1487, also lactating, showed no definite clinical symptoms upon which a diagnosis of aphosphorosis could be made, although they were obviously in very poor condition. The figures for inorganic P of the blood at once suggest the cause of the poor state of nutrition and, irrespective of other evidence, incriminate the pasture.

It is worthy of special note that none of the animals supplied with bone meal suggested malnutrition due to phosphorus deficiency, and that the only cows in which malnutrition actually reached the borderline of clinically recognisable disease (styfsiekte) were the lactating controls. The drain of milk production turned the scale from "poor condition" to "specific disease." This observation is interesting in view of the fact that actual styfsiekte has rarely been diagnosed on this farm before; and in view of the fact that on many farms of the Union the pasture contains just that borderline quantity of phosphorus at which no actual disease comes to awaken the farmer to the real reason for the unthrifty condition of his cattle.

In the following Table II, provisional data are offered for the blood of younger animals; a selection of the first-cross heifers (*loc. cit.* (2)) arranged according to paternal strain.

It will be noted that the same contrast in the "Inorganic Phosphorus" is apparent, although the actual figures run higher than in Table I. The average for the lot supplied with bone meal since weaning is 5·2 mg. inorganic P per 100 c.c. of blood, as against 2·3 mg. for those confined to veld grazing. The average figure 5·2 mg. for heifers approaching two years old is interesting in comparison with the lower average figure of 3·1 mg. for lactating cows (Table I) supplied with the same amount of

[1] Thanks are due to Mr J. Bisschop, B.V.Sc., for opinion on these animals at Vryburg.

Table II. *Analysis of Whole Blood.*

Inorganic elements in milligrams per 100 c.c.

YOUNG HEIFERS. FIRST CROSS FROM SCRUB COWS TO PURE-BRED SIRES.

Bone meal fed animals.

Breed	Africander				Friesland				Red Poll				Sussex			
No. of animal	1850	1954	1843	1847	1904	2013	2001	1916	2084	2029	2019	2015	2033	1905	2035	1917
Age (months)	22	19	22	22	20	19	19	20	17	18	19	19	18	20	18	20
Total P	—	—	15·1	—	15·4	—	—	—	15·9	—	—	—	15·8	—	—	—
Lipoid P	—	—	7·4	—	8·0	—	—	—	8·3	—	—	—	8·3	—	—	—
Inorganic P	4·9	5·3	5·8	4·8	5·9	5·2	5·3	5·0	5·0	4·9	4·8	5·1	5·8	5·4	5·6	5·0
Organic acid-soluble P	—	—	1·8	—	1·5	—	—	—	2·6	—	—	—	1·7	—	—	—

CONTROL ANIMALS.

Breed	Africander				Friesland				Red Poll				Sussex			
No. of animal	1990	2058	1962	1989	1899	1921	1979	1981	1988	2025	2024*	—	1963	1909	1958	2078
Age (months)	19	18	19	19	20	19	19	19	19	18	18	—	19	20	19	18
Total P	—	12·2	14·6	—	11·1	—	—	—	—	—	—	—	—	—	—	—
Lipoid P	—	7·1	8·3	—	7·6	—	—	—	—	—	—	—	—	—	—	—
Inorganic P	2·5	2·3	2·7	2·0	1·4	2·2	2·6	2·2	2·0	2·8	2·0	—	2·3	3·0	2·1	3·0
Inorganic acid-soluble P	—	2·7	3·5	—	2·1	—	—	—	—	—	—	—	—	—	—	—

* Ox.

Table III.

Inorganic elements in milligrams per 100 c.c.

HEIFER CALVES. CROSS BRED FROM SCRUB COWS.

	Calves of bone meal fed mothers								Calves of control mothers							
Breed	Africander		Friesland		Red Poll		Sussex		Africander		Friesland		Red Poll		Sussex	
No. of animal	2350	2333	2284	2369	2349	2334	2275	2421	2336	2395	2439	2351	2269	2307	2295	2391
Age (months)	7	7	7	7	7	7	7	6	7	6	5	7	7	7	7	6
Total P	—	—	—	—	—	—	—	16·0	—	—	—	—	—	—	—	14·5
Lipoid P	—	—	—	—	—	—	—	9·0	—	—	—	—	—	—	—	8·2
Inorganic P	4·9	4·9	4·6	4·5	4·3	4·7	4·3	5·0	4·3	4·7	3·0	4·9	2·7	3·9	2·5	4·0
Organic acid-soluble P	—	—	—	—	—	—	—	2·0	—	—	—	—	—	—	—	2·3

Table IV.

MISCELLANEOUS ANIMALS. BONE MEAL FED.

Type of animal	Transport oxen			Young oxen		Pure-bred Red Poll cows		Best dairy cows			Best beef cows			Bulls	
														Sussex	Red Poll
No. of animal	1452	1330	1451	2031	1794	1824	1820	1424	1427	1268	1250	1260	1320	1188	1183
Total P	—	15·6	—	—	—	—	15·2	13·2	—	—	14·5	—	—	15·2	—
Lipoid P	—	8·4	—	—	—	—	9·0	8·0	—	—	7·7	—	—	8·0	—
Inorganic P	4·1	4·6	4·3	4·7	4·6	3·6	3·6	2·6	2·8	3·1	3·3	3·2	3·5	3·9	3·1
Organic acid-soluble P	—	2·6	—	—	—	—	2·4	2·6	—	—	3·5	—	—	3·2	—

bone meal. The figure 2·3 mg. for control heifers in comparison with 1·5 mg. for control cows is equally interesting. Two reasons for the difference may be suggested; age and the drain upon skeletal reserves during lactation.

The few figures for lipoid phosphorus and organic acid-soluble phosphorus show no marked divergences, the lower total phosphorus of the controls being mainly due to reduction of inorganic phosphorus.

There is no apparent difference due to breed, although it is not inconceivable that minor differences may appear as the heifers come into calf and lactation commences.

Table III presents similar data for still younger animals; first-cross calves by pure sires out of scrub mothers.

The main point of interest is that although there is a tendency towards reduction of inorganic phosphorus in the blood of the control calves, it is not yet pronounced, owing to the fact that weaning is not yet complete. Although at the age of seven months many of the calves are passing over mainly to veld grazing, they still get sufficient milk from their mothers to obviate specific malnutrition. This is in line with the general experience that even in the "Styfsiekte districts" of the Union, calves may thrive quite well until completely weaned.

In general appearance and in weight the calves of the cows receiving bone meal showed a marked superiority over the calves of control mothers and were much more uniform, but the difference in favour of phosphorus supplement was not so striking as in the case of the heifers of Table II, nine months after weaning. In general the character of the unweaned calf bears a definite relation to the extent to which the mother suffered from aphosphorosis. Thus calves 2295, 2439 and 2269 (Table III), which showed the worst development, also show the lowest inorganic P in the blood; and belong to control mothers 1296, 1246 and 1409, respectively (Table I), which themselves showed an exceptionally low inorganic P fraction. Since low phosphorus in the blood is not necessarily correlated with low phosphorus in the milk (reference (1)), but is often correlated with reduced milk yield, the stunting of the calves under consideration is doubtless due to insufficient milk supply from the mothers.

Table IV offers fragmentary comparison of a few animals selected so as to reflect any outstanding differences which might possibly exist within the variety of stock which happened to be available. It records three fully grown transport oxen, two young oxen (Afrikander breed), two pure bred Red Poll cows, three cows picked out from the scrub herd as conforming to "dairy type," three as conforming to "beef type," one

pure bred Sussex bull and one pure bred Red Poll bull; all in receipt of 3 ounces of bone meal daily.

Little comment is required, since the data are meagre and uncharacteristic. The oxen show a range in inorganic P of 4·1 mg. to 4·7 mg. per 100 c.c. of whole blood. The slight differences between the cows of dairy type and of beef type are probably due to differences in milk yield.

SUMMARY.

Data are recorded concerning the phosphorus partition of the blood of cattle grazing over phosphorus deficient pasture of the Union of South Africa. The outstanding characteristic is low inorganic phosphorus, with a correlated reduction in total phosphorus.

When a small ration of bone meal is given to the cattle, comparatively normal figures are shown. Heifers approaching two years in age, supplied with bone meal from weaning onwards, show a normal inorganic P fraction of 5 mg. per 100 c.c. of blood. Control heifers without bone meal show 2·3 mg., or less than half. Control cows may drop to 1 mg., or even lower. Calves of control mothers are normal so long as milk supply is adequate, but may show reduced inorganic P if aphosphorosis of the mother is acute. In general, low inorganic P in the blood is associated with poor condition of the animal. Rapid colorimetric determination of inorganic P in the blood of the grazing animal, easily obtained from the jugular vein, provides a simple means of detecting phosphorus deficiency in the pasture.

Although long-continued phosphorus deficiency leads to the clinically recognisable disease "Styfsiekte," especially in lactating animals, the less pronounced deficiency, manifested as malnutrition and stunting of growth, without direct mortality, is detected by blood analysis with equal certainty.

REFERENCES.

(1) THEILER, GREEN, and DU TOIT (July, 1927). *J. Agric. Sci.* **17**, 291.

(2) ——— ——— ——— (1928). *J. Agric. Sci.* **18**, 369.

(3) GREEN, H. H. (1928). *J. Agric. Sci.* **18**, 372.

(4) THEILER, GREEN, and DU TOIT (May, 1924). Phosphorus in the Live-Stock Industry. Journal Department of Agriculture, Union of South Africa.

(*Received February* 14*th*, 1928.)

STUDIES IN MINERAL METABOLISM. VI.

COMPARISON OF THE BLOOD OF COW AND CALF IN RESPECT TO MINERAL CONSTITUENTS.

By H. H. GREEN and E. H. MACASKILL*.

(Division of Veterinary Services, Onderstepoort, Pretoria.)

In the paper "Minimum Mineral Requirements in Cattle," by Theiler, Green and du Toit (1927), analytical data concerning the mineral constituents of the blood of a calf, born of a cow suffering from aphosphorosis, were recorded, but left over for later consideration.

The high total phosphorus there shown (35 mg. per 100 c.c. of whole blood) and high inorganic phosphorus (8 mg.) were regarded as normal for the calf in view of the earlier findings of Meigs, Blatherwick and Cary (1919), in their striking study of phosphorus and calcium metabolism in relation to milk secretion. These authors had also recorded low lipoid phosphorus for calf plasma, and our own low figure for whole blood was therefore left without discussion at the time. In view of later data, however, that figure must definitely be regarded as abnormal. The other striking features of the blood of this day-old calf, in comparison with the blood of its own mother, were very high organic acid-soluble phosphorus (13·2 mg.), a large phosphorus fraction of unknown character (12·1 mg., the difference between the total and the sum of the other determined fractions), and very high potassium (168 mg. or three times that of the maternal blood).

The calf died a few days after birth, but the issues raised were taken up in relation to normal calf blood. The present paper brings out the characteristic differences in mineral composition between adult bovine blood and the blood of the calf during the first few weeks of life. Tables I and II supply the data.

In procuring these data, sodium citrate was used as anti-coagulant for all determinations except sodium. For this determination oxalic acid was used. The methods used for determination of phosphorus partition were those recorded in paper IV of this series (Green, 1928). Calcium, magnesium, potassium, sodium and chlorine were determined on the trichloracetic filtrate, after dry combustion, by modifications of the now well-known micro or semi-micro methods; calcium volumetrically by

* Temporary assistant responsible for most analyses. For certain of the figures acknowledgments are due to G. J. R. Krige and A. I. Malan.

Table I. *Analysis of Whole Blood.*

Inorganic elements in milligrams per 100 c.c. Haemoglobin by Newcomer Disc.

		Cow No. 389 and its calf						Cow No. 1630 and its calf					Cow No. 1590 and its calf						
Date, 1927		Feb. 15	Feb. 23	Mar. 2	Mar. 17	Mar. 31	May 4	Mar. 5	Mar. 14	Mar. 28	Apr. 20	May 10	Mar. 21	Mar. 22	Mar. 25	Mar. 28	Apr. 2	Apr. 13	June 7
Period after calving		24 hours	8 days	15 days	4 weeks	6 weeks	10 weeks	5 hours	9 days	23 days	6 weeks	9 weeks	5 hours	24 hours	96 hours	7 days	12 days	23 days	10 weeks
Total P	Cow	17·1	16·9	16·1	16·0	16·0	17·5	16·7	15·5	16·2	17·1	16·4	16·8	—	—	—	—	—	16·5
	Calf	36·0	33·6	30·3	28·3	28·1	19·8	28·5	34·3	31·0	23·6	21·4	24·2	26·1	29·8	29·4	29·8	27·5	20·9
Lipoid P	Cow	9·2	9·1	9·2	7·4	7·3	9·1	9·4	7·9	7·9	9·5	9·2	9·0	—	—	—	—	—	9·0
	Calf	8·9	9·2	10·2	12·3	11·9	8·9	11·6	12·3	12·3	10·7	10·5	8·5	8·6	8·8	9·8	9·9	12·2	11·0
Inorganic P	Cow	4·5	4·7	4·3	5·6	4·7	5·2	4·5	4·7	4·6	4·6	4·5	4·4	—	—	—	—	—	4·5
	Calf	5·0	7·4	7·8	8·0	7·5	7·3	5·5	7·8	8·7	6·9	6·8	5·1	5·3	7·[illegible]	7·5	7·6	7·7	6·7
Organic acid-soluble P	Cow	3·4	3·1	2·6	2·8	3·8	3·2	2·9	2·7	3·7	3·0	2·7	3·4	—	—	—	—	—	3·[illegible]
	Calf	13·9	14·5	12·3	8·0	8·7	3·6	10·6	11·8	9·6	5·9	4·1	10·6	11·9	11·9	10·5	10·2	7·2	3·2
Unknown by difference	Cow	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	—	—	—	—	—	Nil
	Calf	8·2	2·5	Nil	Nil	Nil	Nil	0·8	2·4	0·4	Nil	Nil	Nil	0·3	1·4	1·6	2·1	0·4	Nil
Ca	Cow	8·9	9·4	10·2	10·4	10·2	10·5	10·1	10·2	10·0	10·1	10·5	10·6	—	—	—	—	—	10·8
	Calf	9·8	9·8	10·8	10·9	10·6	10·2	10·8	10·6	10·5	10·4	10·8	11·0	—	—	—	—	10·8	10·8
Mg	Cow	3·9	3·8	3·9	3·9	4·0	4·3	4·7	4·2	4·4	4·3	4·2	4·6	—	—	—	—	—	4·7
	Calf	5·0	4·9	4·9	4·6	4·5	4·8	5·1	4·9	4·8	4·6	4·5	4·7	—	—	—	—	4·5	4·7
K	Cow	35	36	34	40	40	35	43	40	40	39	39	43	—	—	—	—	—	39
	Calf	131	132	112	78	56	38	166	135	75	50	34	179	—	—	—	—	89	37
Na	Cow	240	250	248	247	245	250	292	285	282	295	295	275	—	—	—	—	—	275
	Calf	193	198	225	240	225	245	225	215	277	277	280	245	—	—	—	—	230	265
Cl	Cow	300	295	300	300	295	300	305	305	300	305	303	300	—	—	—	—	—	305
	Calf	305	300	295	295	300	302	285	300	300	295	300	305	—	—	—	—	300	330
Haemoglobin	Cow	75	76	85	85	83	83	95	85	89	87	87	125	—	—	—	—	—	110
	Calf	82	85	97	97	95	93	100	93	92	90	85	93	—	—	—	—	94	88

Table II. *Analysis of Blood and Plasma.*

Cow and Calf, 36 hours after Birth.

				Distribution as calculated from relative volumes of corpuscles and plasma, which happened to be the same for cow and calf				Calculated for corpuscles mg. per 100 c.c.	
				Centrifuge method		Direct method			
Element	Animal	Whole blood mg. per 100 c.c.	Plasma mg. per 100 c.c.	Plasma 61	Corpuscles 39	Plasma 74	Corpuscles 26	Centrifuge	Indirect
Total P	Cow	16·5	9·6	5·9	10·6	7·1	9·4	27·2	36·1
	Calf	32·4	13·6	8·3	24·1	10·1	22·3	61·8	85·8
Lipoid P	Cow	9·0	3·6	2·2	6·8	2·7	6·3	17·4	24·2
	Calf	12·5	3·7	2·3	10·2	2·7	9·8	26·2	37·7
Inorganic P	Cow	4·5	6·0	3·7	0·8	4·4	0·1	2·0	0·4
	Calf	7·4	10·0	6·1	1·3	7·4	Nil	3·3	Nil
Organic acid-soluble P	Cow	3·0	Nil	Nil	3·0	Nil	3·0	7·7	11·5
	Calf	9·5	Nil	Nil	9·5	Nil	9·5	24·3	36·5
Unknown P by difference	Cow	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
	Calf	3·0	Nil	Nil	3·0	Nil	3·0	7·7	11·5
Ca	Cow	9·8	13·3	8·1	1·7	9·8	Nil	4·4	Nil
	Calf	10·8	14·8	9·0	1·8	10·9	Nil	4·6	Nil
Mg	Cow	4·3	2·3	1·4	2·9	1·7	2·6	7·4	10·0
	Calf	4·8	2·4	1·5	3·3	1·8	3·0	8·5	11·5
K	Cow	50	16	9·8	40·2	11·8	38·2	103	147
	Calf	187	27	16·0	171	20	167	438	642
Na	Cow	295	370	226	69	274	21	177	81
	Calf	235	303	185	50	224	11	128	42
Cl	Cow	302	405	247	55	300	2	141	7·7
	Calf	245	332	202	43	246	Nil	110	Nil

permanganate titration of oxalate, magnesium gravimetrically as pyrophosphate, potassium volumetrically by permanganate titration of the cobalti-nitrite, sodium gravimetrically as pyroantimonate, and chlorine by the Volhard volumetric method.

In regard to Table II the first two columns require no explanation, since the figures are direct analytical data. The remaining columns, however, are derived by calculation from the relative volumes of plasma and corpuscles in the whole blood, and since two sets of divergent values are shown, some explanation is required.

In the usual method for determining the volume of red blood corpuscles, the blood is centrifuged in a suitably graduated tube at a speed of 3000 revolutions per minute for about 20 minutes, and the volume of red precipitate read off. However useful such a determination may be for comparative purposes, the result cannot be regarded as representing "absolute corpuscular volume," since some plasma must always remain entangled between the compacted corpuscles. In attempting to ascertain the true proportions of corpuscles and plasma, three methods were tried:

(*a*) Adding a suitable quantity of a dye not absorbed by the corpuscles, centrifuging to obtain the tinted plasma, and estimating the plasma volume by colorimetric comparison with plasma to which known quantities of dye were added.

Neutral red, as used for estimating plasma volume *in vivo*, and phenol tetrachlorphthalein, as used for testing liver function, were tried.

(*b*) Diluting the blood with an equal volume of isotonic saline, centrifuging, and determining the refractive index of the diluted plasma; comparing this with the refractive index of plasma from the same blood, diluted with varying quantities of the same saline, and so estimating the "volume per cent. plasma" of the whole blood.

(*c*) Comparing the total nitrogen content of the saline plasma mixture, as obtained under (*b*), with the total nitrogen content of plasma centrifuged off direct.

Of these three methods (*b*) would probably prove most satisfactory if worked out as a method for general use, owing to the rapidity and ease of determining refractive index to the fourth decimal place, and the obviation of possible absorption of dye by the corpuscles in method (*a*). In regard to the limited data of Table II, however, it may be stated that all three methods gave a factor ranging between 1·45 and 1·55 for conversion of "apparent corpuscular volume" (centrifuge) into "true corpuscular volume." Taking the average figure as 1·5, this means that one-third of the volume of "red precipitate" is still plasma lying between

the compacted corpuscles, and that the true corpuscular volume is only two-thirds of the apparent volume. In the particular case under consideration, the two samples of blood recorded in Table II both gave the same figure of 39 volumes per cent. by direct centrifuging, and only 26 volumes per cent. by the indirect methods. Without claiming that the figure 26 is precise, it may nevertheless be accepted as fairly near the truth; and the data marked "indirect method" in Table II be provisionally accepted as representing the approximate distribution of mineral constituents between corpuscles and plasma. The method of calculation will be obvious from inspection of the table itself; determined values per 100 c.c. of plasma multiplied by plasma volume, giving proportion of constituent in the plasma moiety of the whole blood; and deduction of this from the determined values per 100 c.c. of whole blood, giving the proportion of constituent distributed in the corpuscles.

In amplification of the tables it may be added that occasional partial analyses of the blood of calves, between the ages of 9 and 15 months, showed a distribution of phosphorus fractions very similar to that of adult bovine blood, but with a tendency towards somewhat higher inorganic phosphorus. In paper V of this series (Malan, Green and du Toit, 1928) a number of figures for veld-bred cattle of varying ages were given, but in view of the fact that the inorganic phosphorus fraction varies with diet the specific influence of age is not quite clear.

In regard to potassium it may be added that occasional analyses suggest relative constancy in the blood of the same individual at different times, but very great differences in different individual adult cattle.

Surveying both tables together, in the light of these comments, the following provisional generalisations seem justified:

(1) Total phosphorus of the blood of the new-born calf may be over twice that of its own mother. It appears to rise somewhat for the first few days after birth, then falls steadily, so that 10 weeks later the difference may only amount to 15 per cent. After weaning, the difference between the blood of the calf and the blood of the mother may hardly be noticeable at all. Although the total phosphorus of the plasma is also higher in the young calf, the main difference is in the red corpuscles and is largely accounted for by the organic acid-soluble fraction (phosphoric esters).

(2) This organic acid-soluble phosphorus appears to be confined to the corpuscles in both calf and mother, and is over three times as high in the case of the calf at birth. It then falls steadily and after 10 weeks the difference may no longer be noticeable.

(3) The red corpuscles of calf blood may also show an unknown phosphorus fraction, insoluble in acid and probably of nuclear origin. The amount is variable and small, and its occurrence erratic. In one case, however, it reached a high value the day after birth. This fraction has never been noted in appreciable amount in healthy adult cattle.

(4) The lipoid phosphorus fraction in the blood of the calf at birth may be similar in amount to that of the mother, or may be higher. It tends to rise over the first few weeks of life, may remain high for months, or may fall again. It would appear to be distributed about one-third in the plasma and two-thirds in the corpuscles.

(5) The inorganic phosphorus fraction of the blood of the calf at birth is appreciably higher than that of the mother, rises sharply within the first week, begins to fall again during the second month, and even after 10 weeks is still high. After weaning, the figure appears to approach that of adult blood, but in general would seem to run higher in young than in old animals.

The inorganic fraction appears to be confined to the plasma, with very little in the corpuscles.

(6) An outstanding feature of calf blood is its very high potassium content; nearly twice as high for plasma and over four times as high for red corpuscles. The high figure rapidly falls, however, and after 10 weeks calf blood can be regarded as adult in respect to potassium. More than four-fifths of the total potassium may be locked up in the corpuscles. The variation in the potassium content of the blood of adult cattle is greater as between different individuals, than it is within the same individual at different times.

(7) In regard to calcium, magnesium, sodium and chlorine, there are no characteristic differences between blood of calf and blood of mother. Magnesium appears to be distributed about two-thirds in the corpuscles and one-third in the plasma. Sodium is present chiefly in the plasma; calcium and chlorine almost exclusively so.

Since the data presented are limited, the findings in regard to magnesium need confirmation, but there can be no doubt in regard to potassium. The regular fall in potassium content over the first two months of life is unmistakable. The figures recorded for calcium in the whole blood of these South African cattle run about the same as those quoted by Meigs, Blatherwick and Cary (1919) for plasma; our figures for plasma therefore being considerably higher. The behaviour of calf blood in regard to inorganic phosphorus supports their observations on calf plasma. In regard to lipoid phosphorus of calf plasma, our data are too

limited to verify their contention that it is much lower than in adult cattle; but in regard to whole blood, lipoid phosphorus cannot be regarded as low. Working mainly with plasma, they did not observe the high acid-soluble phosphorus fraction, and the occasional appearance of the "unknown fraction," in the corpuscles. Other mineral constituents were not dealt with by them.

In conclusion it should perhaps be emphasised that our data are not derived from pure bred dairy stock of high milk yield, but from veld-bred cattle of mixed ancestry of low milk yield, and not fed for milk production.

REFERENCES.

(1) THEILER, A., GREEN, H. H. and DU TOIT, P. J. (July, 1927). *J. Agric. Sci.* **17**, 291.

(2) MEIGS, E. B., BLATHERWICK, N. R. and CARY, C. A. (January, 1919). *J. Biol. Chem.* **37**, 70.

(3) GREEN, H. H. (1928). *J. Agric. Sci.* **18**, 372.

(4) MALAN, A. I., GREEN, H. H. and DU TOIT, P. J. (1928). *J. Agric. Sci.* **18**, 376.

(*Received February* 14*th*, 1928.)

STUDIES IN MINERAL METABOLISM. VII.

THE UNKNOWN PHOSPHORUS FRACTION OF CALF BLOOD.

BY A. I. MALAN* AND H. H. GREEN.

(*Division of Veterinary Services, Onderstepoort, Pretoria.*)

IN article VI of this series, "Comparison of the Blood of Cow and Calf in Respect to Mineral Constituents" (Green and Macaskill, 1928), the occurrence of an unknown phosphorus fraction in the blood of young calves was discussed; and the probability that it is of nuclear origin was suggested.

In going through the available literature, it became quite apparent that this fraction has been stumbled over in previous blood analyses, but for various reasons not pinned down as a real entity. Perhaps the most striking recent example is to be found in the analyses of human blood corpuscles by Stanford and Wheatley (1925). In one case the difference between "total phosphorus" and "total acid-soluble phosphorus" amounted to 16·9 mg. per 100 c.c., and in another case to 20·1 mg. As a general rule this should correspond to "lipoid phosphorus," but the values for lipin P as actually determined were quite different: 13·1 mg. and 12·7 mg. respectively. There is thus a difference of 3·8 mg. in one case, and 7·4 mg. in the other, to be accounted for. The authors discuss the possibilities of error in extraction with alcohol-ether, and state: "...doubtful whether the differences found are due to incomplete extraction, or to the presence of P compounds which are precipitated by trichloracetic acid, but are not soluble in an alcohol-ether mixture." In our opinion, they were dealing with a real fraction of the kind found by us in calf blood, and now shown to be largely nucleoprotein. This fraction, as will be shown later, constitutes a very large proportion of the total phosphorus in the blood of those animals, such as the fowl and frog, which have nucleated erythrocytes.

Other investigators working with serum or plasma recognise the presence of nuclein phosphorus only in traces. So far back as 1897, Abderhalden recorded 0·0006 per cent. Rona and Takahashi (1913) reported 0·0005 per cent. in horse serum. Greenwald (1913) suspected the presence of protein phosphorus in pig blood, and in a later article

* Webb Research Scholar, from the University of Stellenbosch. Responsible for all experimental work.

(1915) expresses the belief that phosphorised proteins are present both in serum and in whole blood. This was doubted by Bloor (1918), who reported that the "sum of the acid-soluble and lipoid phosphoric acid has in almost all cases been found to be equal to the value for total phosphates, within the limits of experimental error." Meigs, Blatherwick and Cary (1919), after discussing the previous evidence, conclude that protein phosphorus is absent, or only present in negligible traces, in oxalated plasma, and suggest that the small amounts occasionally reported in serum may be due to blood platelets.

In our own analyses of citrated or oxalated mammalian plasma, the sum of lipoid P and total acid-soluble P has always been so close to total P that any divergence has been regarded as due to experimental error. The position is quite different, however, when whole blood is considered. The divergence was there found to be so definite that, although its occurrence was often erratic, there could be no question of dismissing it as experimental error. If other investigators had dealt with whole blood as frequently as they have dealt with plasma, there is little doubt that the existence of a nuclein fraction in mammalian blood would have been established before, or at least an "acid-insoluble fraction other than lipoid." In some cases, as for instance Kay (1925), workers on whole blood have determined acid-soluble P and lipoid P, and assumed that the sum represented the total. In other cases inorganic and lipoid have been determined, and the sum of these deducted from the total to obtain "organic acid-soluble." This of course means that even if a nuclein fraction were present it would escape notice. Only when all three determinations—total P, total acid-soluble P (including inorganic P) and lipoid P—are made, does the "unknown fraction" become apparent.

From the data in the previous article (reference (1)) it appeared that the unknown fraction might be present or absent at birth, but was liable to occur, in erratic fashion and in variable amount, during the first few weeks of life. In order to verify the supposition that the appearance of the unknown fraction was associated with nuclear material, blood smears were prepared from a number of young calves, up to a month old, stained in the usual way, and examined. It was at once noted that erythroblasts, normoblasts and Jolly bodies were by no means uncommon features of calf blood; and that, in general, the "unknown phosphorus fraction" was only noticeable when the presence of nuclear material could be detected in fair amount in a stained blood film. It seems that when the new-born calf commences its own independent metabolism, new erythrocytes thrown into the circulation from the marrow may not always be

fully mature; and that a small proportion of immature precursors containing nuclear material is not uncommon during the first few weeks of life.

The following "composite table," in which fowl blood is inserted for comparison, illustrates the general behaviour. The methods used in obtaining the data were those described by Green (1928). An analysis of the blood of a bovine foetus, three months before full term, is given in the first column, from which it will be noticed that no unknown fraction is shown.

Table I. *Analysis of Whole Blood.*

Inorganic elements in milligrams per 100 c.c.

	Foetus bovine 6 months	Calf at birth	Calf 24 hours old	Calf 3 days old	Calf 12 days old	Calf 10 weeks old	Fowl
Total P	27·5	25·2	26·1	29·8	29·8	20·3	90·4
Lipoid P	7·7	8·5	8·6	8·8	9·9	8·9	14·9
Inorganic P	5·0	5·1	5·3	7·7	7·6	7·3	2·1
Organic acid soluble P	14·8	11·6	11·9	11·9	10·2	4·1	32·9
Unknown P	Nil	Nil	0·3	1·4	2·1	Nil	40·5
Presence of nucleated erythrocytes	Very few	Very few	Few	Frequent	Fairly numerous	Very few	Typically nucleated

The very high proportion of "unknown phosphorus" in fowl blood, amounting to about half the total phosphorus, associated with the typically nucleated corpuscles, leaves no doubt that this is nucleoprotein. The parallelism between the appearance of nucleated corpuscles in small numbers in calf blood and the appearance of the unknown phosphorus fraction is strong evidence that this also is nucleoprotein. Still further evidence is the fact that the unknown fraction is confined to the corpuscles. Analysis of plasma from the fowl in Table I, and from the 12 day old calf, showed none. The same fact is brought out in the analyses of Table II, given below.

CONFIRMATION OF THE PRESENCE OF NUCLEOPROTEIN.

In order to confirm the presence of nucleoprotein, a direct attempt was made to isolate sodium nucleate by the method of Jones (1920) and to demonstrate the presence of purins in this. Fowl blood was taken in the first instance, as containing the unknown fraction in large amount, and calf blood subsequently examined.

For fowl blood a 10 c.c. quantity was precipitated with trichloracetic acid in the usual way, filtered, washed with dilute trichloracetic acid, sucked dry, the brown residue washed into a flask with approximately 80 c.c. of the usual alcohol-ether mixture, and digested under a reflux

condenser for two hours. The whole was then washed into a large centrifuge tube with a little more alchol-ether, centrifuged, and the alcohol-ether pipetted off. After washing twice with alcohol-ether the protein precipitate (now free from acid-soluble P and lipoid P) was treated, according to the method of Plimmer and Scott (1908), with 75 c.c. of 1 per cent. NaOH for 48 hours at 37° C. The brown solution so obtained was filtered, and total phosphorus determined on an aliquot. An amount corresponding roughly to the "unknown fraction" of the original blood was found, thus demonstrating the association of this fraction with the protein precipitate. A test for inorganic phosphorus at this stage showed only traces, thus indicating the absence of phosphoprotein, the phosphorus of which is split off by the Plimmer-Scott procedure. The rest of the filtrate was rendered acid to litmus, heated to boiling, filtered through a hot water funnel, concentrated somewhat, poured slowly (while still hot) into about 400 c.c. of 96 per cent. alcohol and left overnight for separation of sodium nucleate (Jones, 1920). The precipitate so obtained was filtered, washed with 96 per cent. alcohol, finally with absolute alchohol, and dried in a desiccator. The small yield of greyish white powder was then further examined by hydrolysing a portion with 5 per cent. sulphuric acid and testing for purine bases with ammoniacal silver nitrate; also by boiling a portion with 15 per cent. sulphuric acid, adding excess of copper sulphate, and then a saturated solution of sodium bisulphite, to obtain the white copper purine compound ($R . Cu_2O$). In both cases positive tests were obtained, thus demonstrating the presence of nucleoprotein in fowl blood.

The procedure was then repeated with fowl blood, reversing the order of extraction of acid-soluble P and lipoid P; adding the blood to the alcohol-ether mixture in the usual way, washing the precipitated proteins with alcohol-ether, extracting the residue with dilute trichloracetic acid, and then proceeding to the isolation of sodium nucleate. This procedure was found more rapid and a fair yield was again obtained.

A sample of calf blood showing about 3 mg. per 100 c.c. of "unknown P," and a sample of adult bovine blood showing none, were then subjected to similar treatment. In both cases small gelatinous precipitates were obtained on pouring the filtrate (after NaOH digestion) into 96 per cent. alcohol, but only in the case of the calf blood did this precipitate give the purine compound with ammoniacal silver nitrate.

It may therefore be accepted that the calf blood showing the unknown fraction contained nucleoprotein.

In conclusion a few provisional data (Table II) in connection with a

separate investigation which will be reported upon at a later date may be offered to show that this "unknown phosphorus fraction" can appear in human blood and in horse blood as well as in calf blood. Fowl blood is again inserted for comparison, and data given for citrated plasma as well as for citrated whole blood.

Table II. *Analysis of Blood and Plasma.*

Inorganic elements in milligrams per 100 c.c.

	Human		Horse		Calf (7 days old)		Fowl	
	Whole blood	Plasma	Whole blood	Plasma	Whole blood	Plasma	Whole blood	Plasma
Total P	31·1	11·2	30·6	7·8	25·2	15·5	89·1	9·4
Lipoid P	10·3	7·6	10·1	5·2	8·2	5·9	14·4	5·9
Inorganic P	2·8	3·5	2·1	2·6	7·4	9·6	2·2	3·6
Organic acid-soluble P	10·6	0·1	13·6	Nil	6·1	Nil	33·0	Nil
Unknown P by difference	7·4	Nil	4·8	Nil	3·5	Nil	39·5	Nil
Vol. per cent. R.B.C. by centrifuge	42	—	32	—	35	—	36	—

It will be noted that both the organic acid-soluble phosphorus and the nucleoprotein P are confined to the corpuscles and are not shown in the plasma. If the distribution of the inorganic fraction be calculated from the relative volumes of corpuscles and plasma shown by centrifuging, it is found chiefly in the plasma. According to Buell (1923) the inorganic phosphorus fraction in dogs' blood is wholly in the plasma. In Table II the detailed distribution of the various fractions over corpuscles and plasma is not calculated, since no attempt was made to determine the "absolute corpuscular volume" as distinct from the "apparent volume" shown by centrifuging—a point discussed earlier (reference (1)).

SUMMARY.

An unknown phosphorus fraction previously recorded by the authors as frequently present in calf blood, is shown to be nucleoprotein and due to the presence of precursors of fully mature erythrocytes. The same fraction may also appear in small amounts in human blood and in horse blood, and always occurs in very large amount in the nucleated erythrocytes of birds.

REFERENCES.

(1) GREEN, H. H. and MACASKILL, E. H. (1928). Comparison of the Blood of Cow and Calf in Respect to Mineral Constituents. *J. Agric. Sci.* **18**, 384.

(2) STANFORD, R. V. and WHEATLEY, A. H. M. (1925). *J. Biochem.* **19**, 706.

(3) RONA, P. and TAKAHASHI, D. (1913). *Biochem. Z.* **49**, 370.

(4) GREENWALD, I. (1913). *J. Biol. Chem.* **14**, 369; and 1915, **21**, 29.

(5) BLOOR, W. R. (1918). *J. Biol. Chem.* **36**, 49.

(6) MEIGS, E. B., BLATHERWICK, N. R. and CARY, C. A. (1919). *J. Biol. Chem.* **37**, 1.

(7) KAY, H. D. (1925). *Biochem. J.* **19**, 447.

(8) BUELL, M. V. (1923). *J. Biol. Chem.* **56**, 97.

(9) GREEN, H. H. (1928). *J. Agric. Sci.* **18**, 372.

(10) PLIMMER, R. H. A. and SCOTT, F. A. (1908). *J. Chem. Soc.* **93**, 1699.

(11) JONES, W. (1920). *Nucleic Acids.* Monographs on Biochemistry. Longmans, Green and Co. Second edition, p. 103.

(*Received February* 14*th*, 1928.)

STUDIES IN MINERAL METABOLISM. VIII.

COMPARISON OF PHOSPHORUS PARTITION IN THE BLOOD OF CALF FOETUS, SHEEP FOETUS, AND LAMBS, WITH CORRESPONDING MATERNAL BLOOD.

By A. I. MALAN.

(Division of Veterinary Services, Onderstepoort, Pretoria.)

In number VI of this series, "Comparison of the Blood of Cow and Calf in Respect to Mineral Constituents" (Green and Macaskill, 1928), and number VII, "The Unknown Phosphorus Fraction of Calf Blood" (Malan and Green, 1928), data were provided concerning the mineral composition of the blood of the adult cow and the young calf. The present article extends that work and includes a comparison of the phosphorus partition of the blood of lambs as compared with the blood of the mother ewes.

Table I gives the data. The methods of analyses adopted were those recorded by Green (1928). In obtaining the foetal blood, the mother was shot, rapidly opened, the still living foetus at once extracted, and blood taken by cutting across the jugular vein. The heart of the six-month calf foetus continued beating for 15 minutes after removal from the uterus, so that no difficulty was experienced in obtaining sufficient blood (citrated).

The points to which it is desired to draw attention may be arranged as follows:

(1) *Foetal Blood.* The outstanding feature of the blood of the bovine foetus, estimated as between the sixth and seventh month of term, is the definite presence of an organic acid-soluble fraction in the plasma. This may or may not be a characteristic feature of early foetal blood, but it happens to agree with observations made by Plass and Tompkins (1923) on human blood. The high organic acid-soluble fraction in the whole blood is similar to that found in the calf during the early days of life (references (1) and (2)), but all previous data on bovine blood, either calf or adult, indicate that this fraction is characteristic of the corpuscles and is not present in the plasma in more than traces. This confinement to the corpuscles was also noted by Malan and Green in human blood, horse blood, and fowl blood, and is in accordance with the earlier observations on plasma of Greenwald (1916), Bloor (1918), and Stanford and Wheatley (1925).

Table I. *Analysis of Blood and Plasma.*

Inorganic elements in milligrams per 100 c.c.

Haemoglobin by Newcomer disc, calculated to Haldane standard.

	Bovine					Ewes and their lambs						
	Calf foetus 6 months		Mother of foetus	Normal calf 24 hours old		Ewe No. 18157	Lamb 24 hours old	Ewe No. 18185	Lamb 7 days old	Ewe No. 18163	Lamb foetus practically full-term	
	Blood	Plasma	Blood	Blood	Plasma	Blood	Blood	Blood	Blood	Blood	Blood	Plasma
Total P	27·5	11·6	15·0	32·4	13·6	14·1	38·8	16·9	40·9	13·9	29·2	10·7
Lipoid P	7·7	3·7	8·2	12·5	3·6	7·2	10·6	8·4	11·9	7·0	7·5	2·5
Inorganic P	5·0	6·3	1·6	7·4	10·0	3·3	9·0	4·5	8·3	2·7	8·1	8·2
Organic acid-soluble P	14·8	1·6	5·2	9·5	Nil	3·6	12·4	4·0	12·3	4·2	7·3	Nil
Nucleoprotein P	Nil	Nil	Nil	3·0	Nil	Nil	6·8	Nil	8·4	Nil	6·3	Nil
Haemoglobin	65	—	110	82	—	64	98	83	96	—	85	—
Volume per cent. R.B.C.	21	—	—	26	—	—	—	—	—	—	28	—

No nucleoprotein P is shown in the foetal blood, so that the occurrence of this fraction during the first few weeks of life (reference (1)) would seem to be characteristic of the early period of independent metabolism rather than of embryonic life. Otherwise the blood of this six-month foetus, in so far as phosphorus partition is concerned, might well be that of a calf at birth. The high total phosphorus is largely due to the high organic acid-soluble fraction.

The blood of the foetal lamb (last column of Table I) is best left over for consideration in the light of additional data, since on extracting from the uterus it was found to be much older than anticipated—probably within a week of birth. It is, however, interesting to note that the organic acid-soluble phosphorus is confined to the corpuscles, and that a large nucleoprotein fraction is shown. Apparently this nucleoprotein fraction, characteristic of "unripe erythrocytes," can appear in the blood before birth. In this particular case the amount of nucleoprotein P actually shown (6·3 mg.) is surprisingly high in comparison with the proportion of nucleated red cells shown in a stained film of the same blood, and raises the doubt whether the "unknown fraction" is always nuclear material or whether some other "acid-insoluble" phosphorus compound may not occur in the corpuscles.

(2) *Lamb Blood.* The same general characteristics are shown for lamb blood in comparison with the blood of the mother ewe, as already shown for calf blood in comparison with the blood of the mother cow (references (1) and (2)). The total phosphorus is about twice as high for the lamb as for the ewe. The inorganic phosphorus is much higher in lamb blood than in maternal blood. The organic acid-soluble fraction is about three times as high in the lamb as in the mother ewe. A relatively large "unknown P" fraction is present in the red corpuscles of the lamb one day old, and in the lamb seven days old. The lipoid P is generally higher in the blood of the lamb, but (as indicated by the plasma of the full-term foetus) the greater proportion of this is associated with the erythrocytes.

(3) *Inorganic P.* The very low inorganic P (1·6 mg.) of the cow, from which the foetus was taken, is not normal, but is evidence of phosphorus deficiency in the food (Malan, Green, and du Toit, 1928). The cow was not in good condition, but actual aphosphorosis was not suspected, although the blood analysis serves to cast suspicion on the pasture of the farm over which this cow had been grazing. In regard to the three ewes, the values for inorganic P, 3·3 mg., 4·5 mg., and 2·7 mg. per 100 c.c. of blood, respectively, may be normal, but it is equally likely that they are subnormal as a result of subnormal phosphorus content of their

grazing. Further work is required to clear up this point and establish the range of normal variation for the sheep. The very marked difference between the inorganic P of the blood of the ewes (average 3·5 mg.) and of their lambs (average 8·5 mg.) may perhaps be exaggerated by dietary factors.

In regard to the distribution of the inorganic P over plasma and corpuscles, calculation of reliable data is conditioned by an accurate knowledge of the relative volumes of plasma and corpuscles (reference (1)). Even taking the apparent volumes, however, calculation shows practically all the inorganic P to be in the plasma of the calf foetus and of the day-old calf. For the lamb foetus, however, the value in plasma is scarcely higher than in whole blood, and this indicates an even distribution over corpuscles and plasma in this particular case. In all previous analyses of blood samples appreciable amounts of inorganic P have rarely been found in the corpuscles, and since there was no opportunity of repeating the analysis of this foetal blood, the observation may be left in doubt in the meantime.

Summary.

In regard to phosphorus partition, the same general relationship holds between the blood of lambs and of the mother ewes, as between the blood of calves and the mother cows. Total phosphorus is about twice as high in lamb blood as in maternal blood, inorganic phosphorus about twice as high, and organic acid-soluble phosphorus about three times as high. A considerable proportion of an acid-insoluble phosphorus fraction, probably nuclein, may be present in the red corpuscles of lamb blood and may even be present in foetal blood. The organic acid-soluble fraction is confined to the corpuscles, both in young blood and adult blood, but in one case of a six-month calf foetus a small proportion was noted in plasma.

REFERENCES.

(1) Green, H. H. and Macaskill, E. H. (1928). *J. Agric. Sci.* **18**, 384.
(2) Malan, A. I. and Green, H. H. (1928). *J. Agric. Sci.* **18**, 391.
(3) Green, H. H. (1928). *J. Agric. Sci.* **18**, 372.
(4) Plass, E. D. and Tompkins, E. H. (1923). *J. Biol. Chem.* **56**, 309.
(5) Stanford, R. V. and Wheatley, A. H. M. (1925). *Biochem. J.* **19**, 697.
(6) Bloor, W. R. (1918). *J. Biol. Chem.* **36**, 49.
(7) Greenwald, I. (1916). *J. Biol. Chem.* **25**, 697.
(8) Malan, A. I., Green, H. H., and du Toit, P. J. (1928). *J. Agric. Sci.* **18**, 376.

(*Received February* 14*th*, 1928.)

STUDIES IN MINERAL METABOLISM. IX.

THE PHOSPHORUS PARTITION OF BLOOD IN ANAEMIA OF CATTLE AND SHEEP.

By A. I. MALAN.

(*Division of Veterinary Services, Onderstepoort, Pretoria.*)

IN a previous publication by Malan and Green (1928) an "unknown phosphorus fraction," frequently occurring in calf blood and lamb blood during the first few weeks of life, was shown to be due to nucleoprotein associated with the occurrence of nucleated red cells.

In general, therefore, this nucleoprotein P, determined by difference between total P and the sum of total acid-soluble P and lipoid P, would be expected to occur under any conditions which involve increase in the number of cells containing nuclear material. The proportion of leucocytes in blood is so small, in comparison with erythrocytes, that variations in their number would hardly account for appreciable amounts of nucleoprotein. But if even a small percentage of the total red cells is represented by nucleated precursors of the mature erythrocyte, an appreciable amount of nucleoprotein P should show up by the usual micro-methods for determination of phosphorus partition. Since the occurrence of Jolly bodies, normoblasts and erythroblasts is a common feature of anaemia, it was considered of interest to ascertain whether the "unknown P" would be found in cases of anaemia of cattle and sheep.

The following Table I gives the partition of phosphorus compounds in three cases of anaemia; two calves (about a year old) suffering from anaplasmosis, and a sheep suffering from wireworm infection (*Haemonchus contortus*).

Table I.

Inorganic elements in milligrams per 100 c.c. whole blood.

Animal	Calf No. 1121	Calf No. 2230	Sheep
Cause of anaemia	Anaplasmosis	Anaplasmosis	Wireworm (*Haemonchus contortus*)
Haemoglobin (Haldane standard)	42	36	43
Total P	10·7	17·0	13·8
Lipoid P	3·4	5·6	5·1
Inorganic P	3·5	3·2	3·4
Organic acid-soluble P	2·5	7·2	3·7
Nucleoprotein P	1·3	1·0	1·6

Microscopic examination. Nucleated red cells present in fair numbers.

Table II.

Inorganic elements in milligrams per 100 c.c.

Sheep No. 15,851	Blood	Blood	Blood	Blood	Blood	Blood	Blood	Plasma	Blood	Plasma	Blood	Blood	Blood
Date, 1927	March 30	April 2	April 6	April 10	April 13	April 27	April 29	April 29	May 1	May 1	May 3	May 5	May 7
Total P	18·2	18·2	16·5	16·3	14·8	13·1	12·9	6·0	13·4	6·8	12·8	13·0	13·0
Lipoid P	10·3	8·1	7·4	7·2	7·0	5·4	5·5	2·6	5·6	3·3	5·8	5·6	6·5
Inorganic P	4·3	4·4	3·5	4·5	3·7	4·5	3·2	3·4	3·2	3·5	3·0	3·3	3·2
Organic acid-soluble P	3·7	2·9	2·6	2·6	2·7	2·0	2·9	Nil	3·3	Nil	3·3	4·1	3·3
Nucleoprotein P	Nil	2·8	3·0	2·0	1·4	1·2	1·3	Nil	1·3	Nil	0·7	Nil	Nil
Erythrocyte count (millions)	11·1	8·6	6·5	5·0	4·7	3·5	2·7	—	3·7	—	3·9	4·5	5·5
Volume per cent. (corpuscles)	38	31	24	20	19	15	10	—	15	—	16	18	20
Total blood removed, c.c.	—	1000	1500	2500	3000	5850	6350	—	6850	—	Bleeding discontinued		
Nuclear material		Erythroblasts, normoblasts and Jolly bodies abundant			Normoblasts and Jolly bodies			—	—	—	Few Jolly bodies		

It will be noted from Table I that in each case an appreciable nucleoprotein fraction is present; from 1 mg. to 1·6 mg. P per 100 c.c. of blood.

In order to ascertain whether this fraction would appear during blood regeneration following haemorrhage, the phosphorus partition was determined on two normal sheep which were being bled in connection with another experiment. Half a litre of blood was being taken from the jugular vein every second day (estimated at about one-sixth of the total blood in the body), and aliquots for analysis were obtained at these bleedings. Each analysis therefore represents the position two days after the previous haemorrhage. Table II provides the data for sheep No. 15,851.

It will be noted that this sheep tolerated removal of over twice its total blood volume in the course of a month (although not twice its original total of erythrocytes), during which time the red corpuscles dropped from 11·1 million to 2·7 million, as the "balance" between blood loss and blood regeneration. On cessation of bleeding, the regeneration rate brought the number up to 5·5 million within 10 days.

Erythroblasts, normoblasts and Jolly bodies were abundant for the first few bleedings (10 days), and the presence of these was associated with the appearance of 2 mg. to 3 mg. P as nucleoprotein (per 100 c.c.). With continued periodic haemorrhage, however, nucleated red cells diminished despite the falling erythrocyte numbers, with corresponding diminution of nucleoprotein P to 1·3 mg. After cessation of bleeding this fraction rapidly disappeared, indicating that in the regeneration of blood after long-continued bleeding, only mature erythrocytes were being thrown into the circulation. It would seem as if the appearance of nucleated forms is associated with the first stimulus to over-production, rather than with the regeneration process in full swing.

Table III.

Inorganic elements in milligrams per 100 c.c.

Sheep No. 15,786	Blood	Blood	Blood	Blood	Blood	Blood	Blood	Blood	Plasma
Date 1927	March 30	April 2	April 6	April 10	April 13	April 21	April 24	April 29	April 29
Total P	18·4	18·6	16·4	14·9	13·7	13·0	13·0	10·8	6·2
Lipoid P	10·6	8·9	7·3	5·2	5·5	5·7	5·8	4·9	3·3
Inorganic P	4·1	4·2	3·4	3·9	4·0	3·7	3·6	3·4	2·9
Organic acid-soluble P	3·9	4·0	3·3	4·1	3·3	3·6	3·6	2·5	Nil
Nucleoprotein P	Nil	1·5	2·4	1·7	0·9	Nil	Nil	Nil	Nil
Erythrocyte count (millions)	12·0	8·6	5·4	4·6	3·7	2·7	2·2	1·9	—
Volume per cent. (corpuscles)	44	31	23	20	17	—	10	9	—
Total blood removed c.c.	—	500	1500	2500	3000	4350	5850	6350	Death
Nuclear material	Normoblasts and Jolly bodies frequent on April 3 and April 6. Practically absent from April 13 onwards.								

In Table III very similar behaviour is shown by sheep No. 15,786, which died as a result of the final bleeding at a time when the red corpuscles had dropped from the original 12 million down to 1·9 million. Again the nucleoprotein P rises to 2·4 mg. over the first three bleedings, drops to 1·7 mg. over the next two, and to 0·9 mg. after a further removal of 500 c.c. of blood. Thereafter, four further bleedings, bringing the reduced erythrocyte count of 3·7 million down to 1·9 million, are not associated with further appearance of normoblasts or nucleoprotein.

Similar behaviour is shown by the bovine recorded in Table IV; an animal which was being bled, after splenectomy, in connection with an experiment on East Coast Fever (P. J. du Toit). In this experiment 5 litres of blood were withdrawn from the jugular vein twice a week. Samples for analysis were procured at the bi-weekly bleedings, so that the data represent the position three days after the previous withdrawal of blood.

Table IV.

Inorganic elements in milligrams per 100 c.c.

Bovine No. 870 (splenectomised)	Blood	Blood	Plasma	Blood	Blood	Blood	Blood	Plasma
Date 1927	June 15	June 21	June 21	June 24	July 4	July 11	July 14	July 14
Total P	16·8	16·7	10·6	14·0	14·9	12·5	12·4	9·2
Lipoid P	6·9	6·2	4·8	6·7	7·5	6·5	5·6	3·8
Inorganic P	6·3	5·7	5·8	5·6	5·8	5·3	5·6	5·4
Organic acid-soluble P	2·8	2·7	Nil	0·3	1·5	0·6	1·2	Nil
Nucleoprotein P	0·8	2·1	Nil	2·3	0·1	0·1	Nil	Nil
Volume per cent. (corpuscles)	28	24	—	22	21	19	17	—
Total blood removed (litres)	—	5	—	15	25	40	45	—
Nuclear material	—	Normoblasts and Jolly bodies visible			—	—	Very few Jolly bodies	

Corpuscle counts were not made, but the relatively slow drop in volume of corpuscles as recorded by the centrifuge (28 to 17 vols. per cent.) shows that the rate of blood regeneration was rapid. Although the animal was anaemic to begin with (28 vols. per cent. as against an average normal of about 40 vols. per cent.) and 45 litres of blood had been withdrawn between June 15 and July 14, an amount well over the total blood volume of the body (body-weight about 90 lb.), the degree of anaemia produced (17 vols. per cent.) was not extreme. The point of interest in regard to the nucleoprotein fraction, however, is that it rose to 2·1 mg. per 100 c.c. after the first bleeding, to 2·3 mg. after the third, but then practically disappeared over the next four haemorrhages. This suggests

that the appearance of nucleoprotein (erythroblasts, normoblasts, Jolly bodies, cells showing polychromatic staining) is characteristic of the first stimulus to regeneration rather than of rapid regeneration as such.

Apart from the occurrence of nucleoprotein P, a fraction generally overlooked in determining phosphorus partition, the tables also bring out a variety of other points which, however, it is desired to verify before discussing at length. Meanwhile they may merely be noted in passing. The organic acid-soluble fraction, characteristic of the corpuscles and not present in the few plasma analyses recorded, did not, as might have been expected, fall with the drop in numbers of corpuscles. With sheep No. 15,851 it was 3·7 mg. for 11·1 million erythrocytes (March 30) and 2·9 mg. for 2·7 million (April 29). Apparently, as the number decreases each individual erythrocyte carries a heavier load of phosphoric esters. The erratic, but moderate, variations in inorganic P in all the animals are not surprising in view of the fact that the total blood volume was presumably rectified very quickly by fresh plasma irrespective of the formation of fresh erythrocytes. But it is peculiar that under such circumstances the whole blood should sometimes show more inorganic P than the plasma (per 100 c.c.). This would mean an abnormally high amount of inorganic P in the corpuscles, which, in the normal bovine, usually contain little or none. Since the observations on plasma are so limited, however, it is not desired to generalise.

SUMMARY.

In cases of anaemia in cattle and sheep, of infectious origin, parasitic origin, or due to simple haemorrhage, the phosphorus partition of the blood reveals an "unknown fraction," confined to the corpuscles, and evidently nucleoprotein. It is determined by difference between the total phosphorus and the sum of total acid-soluble and lipoid phosphorus. It is associated with the appearance of nucleated red cells (normoblasts and Jolly bodies) and vanishes as they disappear. The amount may make up a considerable proportion of the total P.

REFERENCE.

(1) MALAN, A. I. and GREEN, H. H. (1928). *J. Agric. Sci.* **18**, 391.

(Received February 14th, 1928.)

FURTHER NOTE ON THE CAPILLARY FORCES IN AN IDEAL SOIL.

By R. A. FISHER, Sc.D.
(Rothamsted Experimental Station, Harpenden.)

In a previous paper (2) the author has treated of the statical forces due to capillarity in an ideal soil. That paper was written in order to amend certain erroneous formulae for the static stress in such a soil, previously put forward by W. B. Haines (1). These formulae covered only that range of water content in which the water exists in isolated rings surrounding the points of contact of adjacent soil particles, and after correction, both for the statical errors of the treatment, and for the geometrical approximation employed, it appeared that the cohesive stress ascribable to capillary forces falls off from its limiting value for dry soil at a rate of only a quarter of the rate found by Haines.

Haines had experimented with certain soil-like materials with the intention of measuring the static stress. His method was to cause a rupture in the soil aggregate by the intrusion of a steel wedge, and to ascribe the maximum resistance encountered to the static stress due to capillary forces. The values obtained varied from zero for dry ignited soil to a maximum near to saturation, at every stage increasing with increasing water content. These experimental values are shown on a diagram ((1), Fig. 2); on the same diagram is shown a theoretical curve consisting of (1) a rapidly falling portion based upon the calculations referred to above; and (2) a rising portion curved in harmony with the experimental values and terminated by an abrupt fall at saturation. This latter portion of the theoretical curve seems to be wholly conjectural; an attempt is made in the text to justify its final value by two assumptions (1) that the static stress at saturation may be equated to the pressure deficiency in a liquid filling the soil pores, and (2) that this pressure deficiency will be just great enough to draw a bubble of air between adjacent particles at the surface. This value is termed by Haines the "entry value." The first assumption appeared plausible, and was accepted by the writer; the second appeared untenable, but was not further discussed in view of the probability that the experimental values would have to be re-interpreted upon an entirely different basis. It will be shown in the present note that both assumptions must

be abandoned. The whole of the theoretical curve was thus either definitely erroneous, or conjectural upon an extremely slender basis.

When the values in the calculable portion of the curve were recalculated, it became evident that they were still in complete disagreement with Haines' experimental values, which, it could scarcely be doubted, must represent some real property of the soil aggregate examined, though possibly not its static stress under capillary forces. It is indeed almost impossible to think that this stress could characterise any portion of the aggregate in the neighbourhood of a rupture, for it is the stress under which the soil particles are in their original positions without mutual pressure, and any displacement in their positions must somewhat violently affect the film of moisture connecting them. On rupture, on the other hand, the particles are displaced so far that the connecting film is broken. There is thus little hope of obtaining measurements of the static stress by the method used by Haines, and the contradiction between his observations and the value calculated would be little to be wondered at, even if his material so far agreed in its properties with the theoretical ideal soil.

There is, however, one quantity intimately involved in the mechanics of the ideal soil which conforms in its general behaviour as water content is increased to the experimental values of Haines, namely the minimum work needed to cause rupture. This circumstance led me to suggest "that if these measurements can be equated to any of the mechanical properties of an ideal soil, it is work required to rupture the connecting moisture rather than the static stress exerted by it, that is the subject of measurement" ((2), p. 497).

On this point and some others, Haines has returned to the subject (3) with the claim that "A decision as to other criticisms was left until more conclusive experimental evidence was forthcoming. This has now been obtained by direct measurement of the pressure deficiency, and the results fully confirm the original interpretation of the cohesive measurements."

The new experiments show that the pressure deficiency falls continuously with increasing water content, as must evidently be the case for a series of stable states; the change of pressure deficiency is, however, slow for water contents of 40–90 per cent. of the pore space, rapidly falling to zero as saturation is approached. These observations contain nothing to modify our previous conclusions. The value, however, at which the pressure deficiency passes its point of inflexion, at which point it may be said to be nearly stationary, or decreasing with minimum speed,

seems in his new treatment to be identified by Haines with the "entry value" or pressure deficiency at which a bubble of air will be forced to pass between adjacent particles. It is not clear on what basis this identification is made. The observed point of inflexion occurs long before saturation. The experimental values are about $6T/r$ (where T is the surface tension, and r the radius of the soil particles), while the theoretical entry value of Haines is, by rough but perhaps sufficient reasoning, assigned to the value $12{\cdot}8\ T/r$. It is, of course, easy to ascribe such discrepancy to the differences which certainly exist between Haines' materials and the ideal soil which is the subject of calculation; the experimental particles are not of equal size, they are not, and cannot be, arranged in the arrangement postulated for the ideal soil; and, further, no evidence is adduced that the angle of contact of liquid with soil particle is at, or near to, zero. With these limitations in mind, these measurements cannot be taken either to disprove Haines' theory of a limiting pressure deficiency of 12·8, or, on the other hand, as showing that equilibrium subsequent to coalescence of the liquid rings is possible at higher pressure deficiencies than the value calculated at coalescence, which is 4·53; the latter is an interesting possibility on which Haines relies a good deal, but of which he gives no satisfactory proof. It may be noted that if the entry value is identified, not with the nearly stationary value of the ordinate, but with some point on the rapidly falling portion of the curves above 90 per cent. water content, the numerical discrepancy becomes more pronounced, while the arbitrariness of the identification is more surprising than ever. The measurements, which Haines has obtained of pressure deficiency, although contributing considerably to the problems chiefly considered in his later paper, do not therefore supply any conclusive evidence upon the problem of static stress originally attacked.

The pressure deficiency only enters into the latter question as a basis for justifying the supposed high stress value near to saturation. It was assumed by Haines ((1), p. 532) that at saturation the static stress must equal the pressure deficiency; that this particular assumption is far from accurate may be proved by means of a general theorem applicable to all stages of water content, which would effectively dispose of the notion of a static stress rising to a maximum at saturation, even if it were admitted that the pressure deficiency were absolutely constant up to this point.

The theorem is as follows. The resultant force on a spherical particle of the fluid pressures and surface tensions to which it is exposed is that of a uniform pressure of amount $p + 2T/r$ acting on the dry portions

of its surface, where p is the pressure deficiency of the liquid phase, T the interfacial tension, and r the radius of the sphere.

For proof, it is easy to see that the resultant of a pressure deficiency, p, over the wet portions of the sphere is equal to the resultant of a pressure excess, p, over the dry portions; the effect of the surface tension is probably most simply investigated by imagining the surface film to be continued by a membrane of uniform tension T passing over the dry portions of the sphere; then, such a membrane will evidently exactly balance the tensile force of the interface, and will itself be held in equilibrium by uniform pressure $2T/r$ over the portion of the sphere which it covers. Consequently the resultant of the interfacial forces is equal to that of a uniform pressure $2T/r$ over the dry areas.

The static stress may be at once investigated from the resultant forces; for these will be zero for particles in the middle of a soil mass, but will be inward for particles on the outer layers, so producing a static stress throughout the mass, the inward forces being ascribable to the excess of dry area upon the outer surfaces of the outmost layer of particles. If, therefore, A is the projection of the dry areas on the outmost layer upon a unit area of surface, and α the projection of the corresponding areas of particles within the mass, the static stress may be written as

$$(p + 2T/r)(A - \alpha).$$

One can now see how slender are the opportunities for the stress to increase in any portion of the range, and that it cannot increase steadily up to a large maximum at saturation. For $2T/r$ is constant for all water contents, and p is a quantity which decreases, or in a limiting case remains stationary, with increasing water content; the first factor therefore never increases but usually decreases. Nor can the dry area at the surface be expected to increase with increasing water content, and the only chance of the second factor increasing in any part of the range is that in such a part α should decrease more rapidly than A. The possibilities for this are very limited, for α is much the smaller quantity, and we can at all stages assert that the stress is less than $(p + 2\,T/r)\,A$, a quantity which cannot increase at any stage

If, for close packing, we evaluate A and α at coalescence, we find

$$A = \tfrac{3}{4}, \quad A - \alpha = \frac{\pi}{4\sqrt{2}} = \cdot 5554, \quad \alpha = \cdot 1946.$$

There is thus no possibility of identifying the stress with the pressure deficiency, p, especially at saturation, when the area A must tend to zero.

In view of the above theorem and its consequences, it will be un-

necessary to go into several points in Haines' last paper which indicate that he has misunderstood the criticisms of his original treatment of static stress.

A very simple reason may be given for rejecting the "entry value," not necessarily from the interpretation of Haines' experiments on pressure deficiency, which may be largely influenced by this value, but certainly from the series of pressures at which the soil water is in physical equilibrium with the surrounding atmosphere. For the process by which, according to Haines, air enters or leaves the cells of the soil structure involves the dissipation of energy; a film of liquid is supposed to be pressed upon by the intruding air until it is ruptured, the air then "blows through" the opening so formed; the energy which must be dissipated before mechanical equilibrium can be again established gives rise to a series of jumps, sufficiently sharp even to have visibly affected the manometer in Haines' experiments ((3), p. 273). It will hardly be denied, therefore, that such a rupture involves irreversible processes by which energy is dissipated; and it follows that the corresponding adjustments by reversible changes will take place at a lower value of the pressure deficiency. The agency for such reversible changes of air content being, of course, furnished by the air dissolved in the soil moisture.

SUMMARY.

The new observations of Haines on the pressure deficiency of liquid in a soil-like aggregate confirm the theoretical deduction that the pressure deficiency falls off with increasing water content, but do not justify his belief in a high static stress as saturation is approached.

A theorem is established connecting the static stress at any water content with the pressure deficiency and the dry area of the surface. This, together with general considerations of the energy conditions of physical equilibria, appears to dispose of the two assumptions from which the high values for the cohesive stress at saturation have been deduced.

REFERENCES.

(1) HAINES, W. B. (1925). "Studies in the physical properties of soils. II. A note on the cohesion developed by capillary forces in an ideal soil." *J. Agric. Sci.* **15**, 529–535.

(2) FISHER, R. A. (1926). "On the capillary forces in an ideal soil." *Ibid.* **16**, 492–503.

(3) HAINES, W. B. (1927). "Studies in the physical properties of soils. IV. A further contribution to the theory of capillary phenomena in the soil." *Ibid.* **17**, 264–290.

(*Received August 6th*, 1927.)

THE PROTEIN CONTENT OF GRASS, CHIEFLY MEADOW FOXTAIL (*ALOPECURUS PRATENSIS*), AS INFLUENCED BY FREQUENCY OF CUTTING.

By FRANK T. SHUTT, D.Sc., F.I.C. (*Dominion Chemist*),
S. N. HAMILTON, B.A., and H. H. SELWYN, B.Agr.
(*Division of Chemistry, Dominion Experimental Farm, Ottawa, Canada.*)

Introduction.

It has been known for many years that agricultural grasses become less nutritious as they approach maturity and ripen their seed. The grass plant in its earlier weeks of growth makes a heavier draft on soil nitrogen than later in the season, with the result that its tissues are particularly rich in protein. As the grass continues to grow, the protein, now formed in lessening quantities, is distributed throughout a greater bulk of the plant and thus its percentage in the dry matter is reduced. From a study of the analytical data on record of grasses examined at several stages of growth, it may be summarised that as a grass matures the protein, ash, fat and water decrease while the carbohydrates (nitrogen-free extract) and fibre increase. Further, in addition to the larger percentage in their dry matter of protein and mineral constituents, the leaves and shoots of very young grass are more succulent, palatable and digestible than the leaves of the older plant. These facts have been used in giving advice as to the best period at which to cut for hay, *i.e.* the stage of growth at which the grass will yield the largest amount of digestible matter per acre. This will vary somewhat with different species, but the weight of scientific evidence is in favour of cutting at or shortly after the flowering period. It will thus be seen that chemistry has contributed valuable information in relation to the best time or period for the harvesting of grass for hay.

In recent years much investigatory work has been carried out in England, Wales and Germany on the life-history of grasses, particularly in respect to composition and digestibility. This work has confirmed and greatly extended the earlier results. The application of the facts thus brought out suggested a new scheme—popularly known as close grazing—for the profitable management of pasture lands. It has been most conclusively shown that in the adoption of this plan of pasturing and manuring, the feeding value of pastures may be greatly increased.

The work recorded in this paper presents data as to the protein and dry matter content of grass of one, two and three weeks' growth, contrasting these results with similar data from the same grass cut for hay. The weights of the several cuttings permit the calculation of the total yields of the nutrients for the season per acre. It may therefore be considered a contribution towards the chemistry and economics of the newly proposed close-grazing scheme of pasturing.

Plan of Experiment, with Attendant Influencing Factors.

The field selected for this investigation had been cut for hay for a number of years. For at least thirty years it had not been ploughed, pastured or manured.

The soil was a deep, moderately heavy clay loam with an abundance of humus. The nitrogen content of the surface soil (to a depth of 6 in.) was 0·258 per cent. (water-free basis) and of the subsoil (from 6 to 12 in.) was 0·08 per cent. The surface soil had a *p*H value of 6·39 and a lime requirement of 2000 lb. carbonate of lime per acre (Jones method). The strong vigorous growth of grass gave evidence of a high degree of fertility.

A botanical survey of the area early in May, 1927, revealed a remarkably even "stand" of grass. The dominant grasses were meadow foxtail (*Alopecurus pratensis*) and timothy (*Phleum pratense*), with the former greatly preponderating. Kentucky blue grass (*Poa pratensis*) was present, but in almost negligible amounts. Legumes were not visible. A very few plants of tall buttercup (*Ranunculus acris*) and dandelion (*Taraxacum officinale*) were noticed.

Meadow foxtail is an early perennial grass of good quality, requiring a rich soil, moist climate and three or four years to come to perfection. Though not among the heaviest hay grasses, it is valuable for pastures on account of earliness, rapidity of growth after cutting and rich aftermath.

Four adjacent plots (*A*, *B*, *C*, *D*), each 12 × 24 ft., were laid out on this area. The frequency of cutting adopted was as follows: *A*, weekly; *B*, fortnightly; *C*, every third week; and *D* at stage for hay (seed formed) with one aftermath. *A*, *B*, and *C* were cut with a lawn-mower, leaving a close-cut sward. Every cutting was immediately weighed, sampled and total moisture determined. The remainder of the sample was air-dried, ground and analysed.

The first cuttings unfortunately contained a certain amount of dead grass, a residue from the growth of the previous season. This somewhat affected both the weight and quality of these initial cuttings, adding to

the weight and detracting from the quality. In the case of plot *A*, it was thought advisable to omit from consideration the data of the first two cuttings.

Notes were taken at each cutting of the colour and length of grass and on changes in botanical composition.

The precipitation was recorded weekly throughout the experiment. Between May 19 and September 29, the period of experiment, the precipitation amounted to 14·79 in. The rainfall for June, July and August, the chief growing months, was 11·32 in.—a precipitation at least 2 in. heavier than the ten-year average for this period at Ottawa.

Furthermore, as the data in Table IV (giving weekly precipitations) show, this was a season characterised by a remarkably well-distributed rainfall, no week being without a shower. This feature made the season one particularly favourable to the rapid springing up of fresh growth after cutting.

FREQUENCY OF CUTTING AS AFFECTING PERCENTAGES OF MOISTURE, PROTEIN AND FIBRE.

Moisture.

The data in Table I show a steadily declining percentage of moisture in the grass with the lengthening of the periods between cuttings. The higher dry matter content in the older grass is possibly accompanied by a slight falling off in palatability and digestibility.

Table I. *Moisture Content of Grasses as Cut.*

	Plot *A* 15 cuttings %	Plot *B* 9 cuttings %	Plot *C* 6 cuttings %	Plot *D* 2 cuttings %
Maximum	77·39	75·28	73·87	67·87
Minimum	66·76	68·20	68 52	63·47
Average	73·52	72·38	71·66	65·67

Protein.

The percentages of protein (dry matter basis) of the several cuttings of the four plots are presented in Table II.

The first cuttings from all the plots contained a certain amount of dead grass from the previous year. This fact undoubtedly has lowered the percentages of protein of the first samples from the plots.

Plot A. The percentages of protein of the ten weekly cuttings, June 2 to August 4 inclusive, range from 19·04 to 22·57 with an average percentage of 21·20.

Table II. *Crude Protein (Dry Matter basis).*

Date of cutting 1927	Plot *A* %	Plot *B* %	Plot *C* %	Plot *D* %
May 19	12·47*	—	—	—
27	14·41*	10·70*	—	—
June 2	19·04	—	10·49*	—
9	21·47	15·73	—	—
16	21·80	—	—	—
23	21·00	16·74	15·33	—
30	20·97	—	—	—
July 8	19·36	19·98	—	9·00
14	21·36	—	16·36	—
21	22·57	20·18	—	—
28	22·19	—	—	—
Aug. 4	22·24	20·60	18·40	—
11	—†	—	—	—
18	21·78	18·63	—	—
25	—†	—	17·25	—
Sept. 1	21·50	19·68	—	—
8	—†	—	—	—
15	18·69	17·30	18·52	—
22	—	—	—	—
29	—	—	—	11·32

* Omitted from consideration owing to presence of old and dead grass.
† Growth too short to allow of cutting.

Subsequent to August 4 growth slowed down and it was found necessary to leave the plot two weeks between cuttings. The three cuttings on August 18, September 1 and 15, therefore, represent fortnightly growths. The data for their protein percentages are 21·78, 21·50 and 18·69, averaging 20·66. These figures, it will be observed, are somewhat lower than those for the weekly cuttings, June 2 to August 4, due in large part to the increasing proportion of dandelion, as noted in the botanical observations of this plot from August 4 on. To lend support to this conclusion, the analysis of a sample of dandelion (leaves, with no flower stalks), collected August 20, is presented.

Composition of Dandelion.

	Fresh material %	Dry matter %
Water	83·17	—
Crude protein	2·88	17·12
Crude fat	0·88	5·18
Carbohydrates	8·09	48·04
Fibre	2·15	12·79
Ash	2·83	16·87
	100·00	100·00

The protein content of dandelion, it will be seen, is distinctly lower than that of cuttings essentially composed of young grass.

Plot B. Omitting, as in the discussion of plot *A*, consideration of the

data of the first cutting (May 27), for the reason already advanced, the range of protein for these fortnightly cuttings, June 9 to September 15 inclusive, is from 15·73 to 20·60 per cent., the average being 18·60 per cent.

Plot C. Again disregarding the first cutting, the protein content of the several collections from this plot cut every third week, June 23 to September 15 inclusive, furnishes the following figures: minimum 15·33, maximum 18·52 and average 17·17 per cent.

Plot D. This plot was first cut July 8, when the grass was at a stage of growth considered best for hay: the seeds of the meadow foxtail were fully formed but not ripe and the timothy was in flower. A second cutting —the aftermath—was made on September 29. This represented twelve weeks' growth, the grass showing a small number of stalks in bloom and the red clover a few plants with ripe seeds.

The percentage of protein of the July cutting was 9·00 per cent. This probably would have been slightly higher but for the presence of the small amount of dead grass of the previous season's growth.

The "aftermath," as might be expected, showed a higher protein content, viz. 11·32 per cent.

The foregoing data clearly prove that frequency of cutting markedly influences the protein content: the shorter the period of growth, the higher the percentage of protein. The following figures, summarised from this work, show at a glance the decrease in protein associated with or following the decrease in frequency of cutting.

Frequency of cutting	Protein (dry matter basis) %
Cut every week (ten cuttings)	21·20
„ two weeks (eight cuttings)	18·60
„ three weeks (five cuttings)	17·17
Cut for hay, with aftermath	10·16

Fibre.

The percentage of fibre and its digestibility markedly influence the nutritive value of grass; as a grass matures and ripens its seed, it becomes less valuable by reason of the increasing amount and lower digestibility of its fibre. The present work indicates that frequency of cutting affects the fibre content; the longer the period of growth, the higher the percentage of fibre and *vice versa.* It is evident that frequent cutting results in the production of a grass which in respect to nutritive value has the characteristics of young grass—high protein and low fibre. The fibre results for this series are as follows:

Table III. *Crude Fibre (Dry Matter basis).*

Date of cutting 1927	Plot *A* %	Plot *B* %	Plot *C* %	Plot *D* %
May 19	25·28	—	—	—
27	25·39	26·74	—	—
June 2	24·00	—	26·65	—
9	21·57	25·24	—	—
16	20·16	—	—	—
23	20·53	22·46	27·13	—
30	22·36	—	—	—
July 8	20·87	23·15	—	32·90
14	19·12	—	23·74	—
21	19·87	21·81	—	—
28	18·48	—	—	—
Aug. 4	18·88	20·96	23·56	—
11	—*	—	—	—
18	16·56	17·47	—	—
25	—*	—	18·22	—
Sept. 1	16·56	17·39	—	—
8	—*	—	—	—
15	15·17	15·52	17·64	
22	—	—	—	—
29	—	—	—	24·40

* Growth too short to allow of cutting.

The trend in respect to the general relationship of period of growth to fibre content may be gathered from a casual inspection of the foregoing table; the specific relationship as observed from this work is more clearly brought out by the following summary:

Frequency of cutting	Fibre (dry matter basis) %
Cut every week (ten cuttings)*	19·38
,, two weeks (eight cuttings)	20·50
,, three weeks (five cuttings)	22·06
Cut for hay, with aftermath	28·65

* This datum, 19·38, is the average from the cuttings June 2 to August 4; if the results from the last three cuttings of the plot, which were fortnightly, are included, the average percentage of fibre becomes 18·80. This low figure is due to the development of dandelion from August 4 on; reference to the analysis of this plant will show a percentage of 12·79 for fibre.

Frequency of Cutting as affecting amounts of Dry Matter and Protein per Acre.

The data so far considered have shown that shortening the period of growth increases the nutritive value of a grass; does the same procedure result in the production of a greater weight of nutrients per acre? Every cutting of the plots was weighed and in consequence this experiment permits a reply to this enquiry.

Dry Matter.

In Table IV data are presented for the weight per acre of the fresh grass and dry matter from the several plots. The table also gives the weekly rainfall throughout the experiment, the recorded data being for the precipitation of the week preceding the date of cutting.

Table IV. *Weight of Grass (as Cut) and Dry Matter per Acre.*

		Plot *A* Cut weekly Weight in pounds per acre		Plot *B* Cut every two weeks Weight in pounds per acre		Plot *C* Cut every three weeks Weight in pounds per acre		Plot *D* Cut for hay, with aftermath Weight in pounds per acre	
Date of cutting 1927	Precipitation	Grass as cut	Dry matter	Grass as cut	Dry matter	Grass as cut	Dry matter	Grass as cut	Dry matter
May 19	—	5898·7	1919·0	—	—	—	—	—	—
27	1·51	624·0	180·0	6493·0	1965·0	—	—	—	—
June 2	0·55	208·0	46·7	—	—	7450·0	2281·0	—	—
9	1·25	359·2	81·7	794·3	227·0	—	—	—	—
16	1·32	226·9	52·9	—	—	—	—	—	—
23	0·35	226·9	53·7	992·4	234·5	2458·0	641·5	—	—
30	1·20	180·0	45·4	—	—	—	—	—	—
July 8	1·37	302·6	83·2	832·2	214·8	—	—	10890·0	3499·0
14	0·27	189·1	46·9	—	—	1598·0	420·6	—	—
21	0·67	170·1	45·3	473·5	131·6	—	—	—	—
28	2·45	226·5	72·6	—	—	—	—	—	—
Aug. 4	0·24	170·2	45·4	907·5	224·0	2401·1	627·7	—	—
11	0·37	*	*	—	—	—	—	—	—
18	0·62	321·4	86·2	501·0	142·2	—	—	—	—
25	0·23	—*	—*	—	—	501·5	160·3	—	—
Sept. 1	0·98	340·3	96·8	463·2	125·6	—	—	—	—
8	0·11	*	*	—	—	—	—	—	—
15	0·70	189·1	62·0	255·2	78·7	586·1	172·5	—	—
22	0·32	—	—	—	—	—	—	—	—
29	0·28	—	—	—	—	—	—	4631·1	1812·0

* Growth too short to allow of cutting.

The data for rainfall are rather unusual in that they show that there was not one week between May 19 and September 29 without rain. The liberal and well-distributed rainfall which characterised this season was undoubtedly a most important factor towards maintaining a steady growth of grass and would, we may conclude, be particularly favourable to the returns from plots *A*, *B* and *C*.

Though certain of the cuttings indicate a more or less definite relation between growth and rainfall, it is evident from the data that other factors, *e.g.* temperature and sunshine, have also had a potent effect on growth.

It is of interest to note that the growth (weight of grass produced) on a unit area does not vary directly with the length of the growing

period. It will be observed that the sum of two successive weekly cuttings does not equal—indeed is always less than—the weight of grass from a fortnightly cutting—the plots being adjacent and the samples grown simultaneously. Over the six weeks' interval, June 30 to August 4 inclusive, the following data from the grass of plots *A*, *B* and *C*, calculated to weights per acre, were obtained:

	No. of cuttings	Grass as cut lb.	Dry matter lb.
Plot *A*, cut weekly	6	1239	339
„ *B*, cut fortnightly	3	2213	570
„ *C*, cut every third week	2	3999	1048

This cumulative effect may possibly be explained on the hypothesis that as the leaf surface develops, the plant's physiological activity or power to grow increases geometrically rather than arithmetically.

Considering the total yields of the plots for the season, plot *D* cut for hay, with aftermath, gave the heaviest weight both of grass as cut and dry matter. Under the conditions of this experiment, with a period of frequency of cutting ranging from one week to three weeks, the total yields increase as the intervals between cuttings lengthen. This is well brought out in the following summary:

Seasonal Yields per Acre: Grass as cut and Dry Matter.

Plot	Grass as cut lb.	Dry matter lb.
A (cut weekly)	9633	2918
B (cut fortnightly)	11712	3344
C (cut every third week)	15004	4304
D (cut for hay, with aftermath)	15503	5311

Protein.

The amounts of protein, per acre, in the several cuttings are given in Table V.

It was pointed out when discussing dry matter yields that plots *B* and *C* produced heavier yields than *A*—the yields being for the same period of growth. The same is true for protein, as is shown in the following summary for the period June 30—August 4.

	No. of cuttings	Protein per acre lb.
Plot *A*, cut weekly	6	74
„ *B*, cut fortnightly	3	116
„ *C*, cut every third week	2	184

Table V. *Weight of Protein per Acre.*

Date of cutting 1927	Plot *A* Cut weekly lb.	Plot *B* Cut every two weeks lb.	Plot *C* Cut every three weeks lb.	Plot *D* Cut for hay, with aftermath lb.
May 19	239·2	—	—	—
27	25·8	210·3	—	—
June 2	8·9	—	239·2	—
9	17·5	35·7	—	—
16	11·5	—	—	—
23	11·3	39·3	98·3	—
30	9·5	—	—	—
July 8	17·8	42·9	—	314·6
14	10·0	—	68·8	—
21	10·2	26·7	—	—
28	16·1	—	—	—
Aug. 4	10·1	46·2	115·5	—
11	—*	—	—	—
18	18·8	24·7	—	—
25	—*	—	16·8	—
Sept. 1	20·8	13·6	—	—
8	—*	—	—	—
15	11·7	26·5	31·9	—
22	—	—	—	—
29	—	—	—	205·1

* Growth too short to allow of cutting.

The season's weights of protein, as resulting from the several plots, are of particular interest. The figures are as follows:

Seasonal Yields per Acre: Protein.

	Protein lb.
Plot *A*, cut weekly	439
,, *B*, cut fortnightly	466
,, *C*, cut every third week	571
,, *D*, cut for hay, with aftermath	520

It is significant that plot *C*, cut every third week, furnished the largest amount of protein per acre.

Second in order is *D*, cut as hay, with aftermath. It owes its position, in a large measure, to its very heavy aftermath enriched by a comparatively high protein content.

Plot *A*, cut weekly, in respect to protein yield ranks last in the series, notwithstanding that its protein concentration was the highest. This position is due to its low yields of grass, and these in turn may possibly be attributed to a disturbance of the proportion of leaf to root necessary to the normal development of the plant following a too frequent cutting. It would seem only natural to conclude that the too frequent removal of foliage would result in a depression of the general vigour and vitality of the plant. It is in the acceptance and development of this hypothesis that the high ranking of *C* probably finds an explanation.

The whole area has been dressed this autumn (October) with a mixture of superphosphate, muriate of potash and sulphate of ammonia. It is the intention to continue the investigation next season, making several applications of available nitrogen and commencing the cuttings at an earlier date than was possible this year.

Digestible Protein.

It may be safely assumed that grass as cut for hay possesses a lower coefficient of digestibility than very young grass; the evidence for this assumption is ample and satisfactory. There are not, however, on record any coefficients which can be strictly applied to the several cuttings of meadow foxtail as analysed in this enquiry. It is impossible, therefore, to calculate precisely the amounts of digestible protein produced in the season by the several plots. It is probably justifiable, however, as between *C* and *D*, to conclude that plot *C* (cut every third week), with its higher total of protein—protein undoubtedly more digestible than that of plot *D*, cut for hay—has yielded the greater amount of digestible protein.

References.

Woodman *et al.* (1926). Nutritive Value of Pasture. *J. Agric. Sci.* **16**, 205.

—— (1927). Nutritive Value of Pasture. *J. Agric. Sci.* **17**, 209.

Nitrogenous Manuring of Pastures. *J. Min. Agric.* September, 1926, p. 498.

Stapledon, R. G. Characters which determine the Economic Value of Grasses. Part I. *J. Min. Agric.* March, 1927, p. 1083.

—— Characters which determine the Economic Value of Grasses. Part II. *J. Min. Agric.* April, 1927, p. 11.

Bruce, A. B. The Grassland Conference at Cambridge. *J. Min. Agric.* June, 1927, p. 201.

(*Received February* 16*th*, 1928.)

DIGESTIBILITY TRIALS WITH POULTRY.

II. THE DIGESTIBILITY OF "WEAK" AND "STRONG" WHEATS, AND THEIR VALUE FOR POULTRY FEEDING.

III. THE DIGESTIBILITY OF "WHOLE" AND "FLAKED" MAIZE.

By E. T. HALNAN, M.A.

(Poultry Nutrition Section, Animal Nutrition Institute, School of Agriculture, Cambridge.)

II. THE DIGESTIBILITY OF "WEAK" AND "STRONG" WHEATS, AND THEIR VALUE FOR POULTRY FEEDING.

THE main bulk of wheat produced in England has hitherto been chiefly utilised by the bread and biscuit trades, and the market prices of the different varieties of wheat have consequently been determined by the suitability of these varieties for use in these trades. From the miller's standpoint, wheats are broadly classified into "strong" and "weak" wheats in accordance with the baking quality of the flours produced from them, flour from "strong" wheats giving rise to large well-piled-up loaves of high quality, flour from "weak" wheats giving rise to close-textured "sad" looking loaves of poor quality. This difference of behaviour in the oven was reflected in the prices paid for the wheats, "strong" wheats always commanding a substantial premium in the wheat market. To within comparatively recent years the chief varieties of wheat grown in England were "weak" wheats, since "strong" wheats gave poor yields when grown under English conditions. Prof. Sir R. H. Biffen devoted his energies to remedying this defect, and has produced several varieties of "strong" wheat which give excellent yields under English conditions while still retaining that quality of strength to which the miller rightly attaches so much importance. The result is that large quantities of English grown "strong" wheats are now being produced, the energies of producers and breeders being directed towards producing wheats which will be readily purchased by the millers.

The continuous extension and development of the poultry industry has introduced another factor in the home wheat trade, and the purchase of wheat for poultry feeding purposes is becoming of increasing importance. The wheat required for the poultry livestock of England and Wales, on a conservative estimate, represents 25 per cent. of the total home supply, and since the poultry industry is willing to pay as good

a price as the miller for wheat, this alternative market appears to merit the attention of the home producer. In view of this demand for wheat for poultry feeding, it appeared desirable to ascertain whether "weak" and "strong" wheats were equally suitable as sources of supply for poultry feeding, and with this object in view a series of digestibility trials on "weak" and "strong" English grown wheats were undertaken. The wheats used for this purpose were Little Joss, Yeoman II, Bearded Rivett and Swedish Iron, a foreign class of wheat Durum being also included for comparative purposes.

Little Joss and Yeoman II form wheats of the "strong" type, and Swedish Iron and Bearded Rivett form wheats of the "weak" type.

The experimental data and results of digestibility trials with Little Joss and Yeoman II are recorded in a previous communication (1).

The series of trials recorded below were carried out on White Leghorns, using the same experimental and analytical procedure as are given in the communication above referred to (1).

Experimental data of digestibility trials.

Exp. III. Period of experiment, 16 *days. Food fed,* 1760 *gm. per bird.*

Table I. *Average composition of Swedish Iron wheat.*

Moisture	11·58 %	Ether extract	2·27 %
Protein	10·06	Fibre	1·69
N-free extract	72·93	Ash	1·47

Table II. *Average composition of mixed excreta in gm. actual weight.*

Bird	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	moniacal nitrogen	Ether extract	Fibre	Ash
1	328·40	296·16	28·13	19·63	2·30	25·29	26·18	32·24
2	322·35	290·48	26·39	19·17	2·50	25·16	26·78	31·87

Digestibility coefficients of Swedish Iron wheat.

Bird 1.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1760 gm. wheat contain	1530·32 gm.	28·34 gm.	39·95 gm.	29·74 gm.	1283·6 gm.
Dung contains	214·49	3·07	23·82	26·18	145·3
Digested	1315·83	25·27	16·13	3·56	1138·3
Dig. coefficient	88·7 %	89·3 %	40·4 %	11·9 %	86·2 %

Bird 2.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1760 gm. wheat contain	1530·32 gm.	28·34 gm.	39·95 gm.	29·74 gm.	1283·6 gm.
Dung contains	210·63	1·59	23·70	26·78	150·2
Digested	1319·69	26·75	16·25	2·96	1133·4
Dig. coefficient	86·2 %	94·4 %	40·7 %	9·9 %	88·3 %

Exp. IV. Period of experiment, 16 *days. Food fed,* 1760 *gm. per bird.*

Table III. *Average composition of Bearded Rivett wheat.*

Moisture	11·56 %	Ether extract	1·83 %
Protein	8·75	Fibre	1·64
N-free extract	74·60	Ash	1·62

Table IV. *Average composition of mixed excreta in gm. actual weight.*

Bird	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Am-moniacal nitrogen	Ether extract	Fibre	Ash
1	296·38	261·38	23·56	14·69	2·32	19·01	25·43	35·06
2	320·26	284·73	23·76	14·05	2·11	20·14	30·08	35·53

Digestibility coefficients of Bearded Rivett wheat.

BIRD 1.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1760 gm. wheat contain	1528·03 gm.	24·64 gm.	32·21 gm.	28·86 gm.	1312·96 gm.
Dung contains	198·08	4·16	17·87	25·43	128·78
Digested	1329·95	20·48	14·34	3·43	1184·18
Dig. coefficient	87·0 %	83·1 %	44·5 %	11·1 %	90·2 %

BIRD 2.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1760 gm. wheat contain	1528·03 gm.	24·64 gm.	32·21 gm.	28 86 gm.	1312·96 gm.
Dung contains	224·76	5·36	19 06	30·08	142·12
Digested	1303·27	19·28	13·15	− 1·22	1170 84
Dig. coefficient	85·3 %	78·2 %	40·8 %	—	89·2 %

Exp. V. Period of experiment, 8 *days. Food fed,* 880 *gm. per bird.*

Table V. *Average composition of Durum wheat.*

Moisture	13·28 %	Ether extract	2·94 %
Protein	12·63	Fibre	1·67
N-free extract	67·96	Ash	1·52

Table VI. *Average composition of mixed excreta in gm. actual weight.*

Bird	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Am-moniacal nitrogen	Ether extract	Fibre	Ash
1	169·92	155·43	18·93	13·41	1·32	10·27	15·37	14·49
2	188·76	171·67	16·30	11·74	1·10	13·31	15·53	17·09

Table VI (*continued*).

Digestibility coefficients of Durum wheat.

BIRD 1.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
880 gm. wheat contain	749·76 gm.	17·78 gm.	25·87 gm.	14·70 gm.	598·05 gm.
Dung contains	100·56	2·10	9·28	15·37	62·78
Digested	649·20	15·68	16·59	– ·67	535·27
Dig. coefficient	86·6 %	88·2 %	64·1 %	—	89·5 %

BIRD 2.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
880 gm. wheat contain	749·76 gm.	17·78 gm.	25·87 gm.	14·70 gm.	598·05 gm.
Dung contains	123·85	1·63	12·45	15·53	85·68
Digested	625·91	16·15	13·42	– ·83	512·37
Dig. coefficient	83·5 %	90·8 %	51·9 %		

Table VII. *Average digestibility coefficients of English grown wheats.*

Wheat	Organic matter %	Protein %	Ether extract %	Fibre %	N-free extract %
Yeoman II	86·2	86·8	52·1	0·0	89·1
Little Joss	86·4	86·5	35·8	4·8	89·3
Durum	85·0	89·5	58·0	0·0	87·6
Swedish Iron	87·4	91·8	40·5	10·9	87·2
Bearded Rivett	86·1	85·6	42·6	3·8	89·7
Average of all varieties	86·2	88·0	45·8	3·9	86·9
*Digestibility by ruminants	—	74	72	59	93
*Digestibility by pigs	—	80	70	60	83
(2) Average of all varieties (34) by poultry	—	74·0	47·1	8·7	88·9

* Henry and Morrison, *Foods and Feeding.*

Several important facts emerge from the experimental data given above. Firstly, provided that the wheat is not intended as the sole source of the dietary, "weak" wheats are, so far as digestibility determinations can show, equally effective as a source of food nutrients as "strong" wheats. In other words, the chief consideration of the wheat grower growing for the poultry feeding market should be yield per acre irrespective of strength. Secondly, except for ether extract and fibre, poultry compare very favourably with pigs and ruminants in their capacity to deal with wheat. Thirdly, comparison of the experimental data given above with the average of those already recorded in the literature dealing with the digestibility of wheat by poultry indicates good agreement so far as the digestibilities of the organic matter, ether extract, fibre, and nitrogen-

free extract are concerned. A consistent difference is shown with regard to the protein digestibility, and this is to be attributed to the method of calculation used. In the above experiments, the Katayama method has been followed. The Katayama method has been criticised on the grounds that the formulae used have been derived from experiments carried out on one operated bird (2), and it is evident that more work is necessary before the Katayama method can be accepted as a standard in general practice. Calculated on the old methods, the average digestibility coefficients for protein on the wheats used in these trials are as follows: Yeoman II 77·0 per cent., Little Joss 76·6 per cent., Swedish Iron 80·7 per cent., Bearded Rivett 71·2 per cent., and Durum 78·5 per cent. Average of all varieties 76·8 per cent. This figure compares very favourably with the average figure given in previously recorded trials, *i.e.* 74·0 per cent.

It is the intention of the author to carry out an investigation on the Katayama method, since the advantages offered by this method are such that it is undesirable to abandon it unless and until further work shows it to be untenable.

SUMMARY.

(1) Digestibility trials with wheats, carried out with White Leghorn cockerels, indicate that "weak" and "strong" wheats are equally suitable as sources of supply of food nutrients for poultry.

(2) In the production of wheat for poultry feeding, yield rather than strength should be the primary aim of the grower.

(3) Further research work on the Katayama method of estimating the digestibility of poultry feedingstuffs is indicated.

LITERATURE.

(1) HALNAN, E. T. *J. Agric. Sci.* **16**, 451–458.

(2) FRAPS, G. S. *Bulletin* **372**. Texas Agricultural Experiment Station, U.S.A.

III. THE DIGESTIBILITY OF "WHOLE" AND "FLAKED" MAIZE.

Maize, either "whole" or "flaked," forms a common ingredient of poultry dietaries, "flaked" maize being a popular ingredient in poultry and chick mashes. In view of the extent to which this grain is used by poultry keepers, it was considered desirable to ascertain the digestibility of both "whole" maize and "flaked" maize. The primary object of including "flaked" maize in the trials was to ascertain whether the process used in producing "flaked" maize improved its digestibility. As is well known, "flaked" maize consists of maize softened by a process of steam cooking and subjected to pressure through hot steel rollers. As the result of this treatment, the maize forms a highly attractive looking product consisting of lemon yellow thin flakes. By the courtesy of Messrs R. and W. Paul, Ltd. of Ipswich, samples of "flaked" maize and "whole" maize used for the production of "flaked" maize were placed at our disposal, thus enabling a true comparison to be drawn between the digestibility of maize in a raw state and maize in the "flaked" state.

Moreover, maize and "flaked" maize from the same source had already been used in determining the relative digestibility and nutritive value of these products in pig digestibility trials, and so presented a unique opportunity of a strict comparison of the relative digestibility of foods by pigs and poultry. Two White Leghorn cockerels were used for the trials. In the case of the "whole" maize, the experimental period lasted over a period of 16 days, 100 gm. of maize being fed to each bird daily. In the case of the "flaked" maize, the experimental period only lasted 12 days, as it was found impossible to carry out a longer period of test using this material as a sole source of diet. The usual plan of experiment and analytical procedure already outlined was adopted.

EXPERIMENTAL DATA OF DIGESTIBILITY TRIALS.

Exp. X. Period of experiment, 16 *days. Food fed,* 1600 *gm. per bird.*

Table I. *Average composition of Yellow Plate maize.*

Moisture	12·76 %	Ether extract	4·97 %
Protein	9·36	Fibre	1·55
N-free extract	69·98	Ash	1·38

Table II. *Average composition of mixed excreta in gm. actual weight.*

Bird	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Ammoniacal nitrogen	Ether extract	Fibre	Ash
1	285·69	258·87	23·68	13·44	1·79	17·76	22·63	26·82
2	322·04	290·91	25·07	17·38	1·60	19·47	24·51	31·13

Table II (*continued*).

Digestibility coefficients of Yellow Plate maize.

BIRD 1.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1600 gm. maize contain	1373·8 gm.	23·97 gm.	79·52 gm.	24·80 gm.	1119·7 gm.
Dung contains	202·4	6·37	16·75	22·63	123·2
Digested	1171·4	17·60	62·77	2·17	996·5
Dig. coefficient	85·3 %	73·4 %	78·9 %	8·7 %	89·0 %

BIRD 2.

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1600 gm. maize contain	1373·8 gm.	23·97 gm.	79·52 gm.	24·80 gm.	1119·7 gm.
Dung contains	220·4	3·44	18·20	24·51	156·2
Digested	1153·4	20·53	61·32	0·29	963·5
Dig. coefficient	84·0 %	85·7 %	77·1 %	1·2 %	86·0 %

Exp. XI. Period of experiment, 12 *days. Food fed,* 1200 *gm. Bird* 2, 1150 *gm. Bird* 1.

Table III. *Average composition of "flaked" maize.*

Moisture	13·07 %	Ether extract	1·78 %
Protein	9·50	Fibre	0·41
N-free extract	74·82	Ash	0·42

Table IV. *Average composition of mixed excreta in gm. actual weight.*

Bird	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Ammoniacal nitrogen	Ether extract	Fibre	Ash
1 L.S.	116·16	99·88	13·80	9·38	0·84	5·04	5·24	16·28
2 L.S.	104·93	90·70	12·32	9·27	0·77	3·12	5·19	14·23
2 W.L.	120·91	112·43	13·70	8·60	1·40	5·50	5·38	8·48

Digestibility coefficients of "flaked" maize.

BIRD 1. (Light Sussex cockerel.)

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1150 gm. "flaked" maize contain	994·9 gm.	17·48 gm.	20·47 gm.	4·71 gm.	860·43 gm.
Dung contains	61·8	2·14	4·36	5·24	38·87
Digested	933·1	15·34	16·11	—	821·56
Dig. coefficient	93·8 %	87·8 %	78·7 %	—	95·5 %

Table IV (*continued*).

Bird 2. (Light Sussex cockerel.)

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1200 gm. "flaked" maize contain	1038·1 gm.	18·24 gm.	21·36 gm.	4·92 gm.	897·84 gm.
Dung contains	53·2	0·83	2·44	5·19	40·41
Digested	984·9	17·41	18·92	—	857·43
Dig. coefficient	94·9 %	95·4 %	88·5 %	—	95·5 %

Bird 2. (White Leghorn cockerel.)

	Organic matter	N in crude protein	Ether extract	Crude fibre	N-free extract
1200 gm. "flaked" maize contain	1038·1 gm.	18·24 gm.	21·36 gm.	4·92 gm.	897·84 gm.
Dung contains	75·2	2·29	4·83	5·38	50·71
Digested	962·9	15·95	16·53	—	847·13
Dig. coefficient	92·8 %	87·4 %	77·4 %	—	94·4 %

Discussion and summary of results.

A review of the existing literature on the digestibility of "whole" maize by poultry showed considerable variation in the results of digestibility determinations on this material. Thus, the digestibility of the protein of maize varied from 47·5 to 95·6 per cent. (average 74·9 per cent.), of fibre from 0 to 41·4 per cent. (average 14·8 per cent.), of N-free extract from 86·6 to 95·7 per cent. (average 90·1 per cent.), and of fat from 67 to 95·2 per cent. (average 85·1 per cent.). In the trials now reported, the average digestibility coefficients obtained were as follows: Organic matter 84·6 per cent., protein 79·5 per cent., fat 78·0 per cent., N-free extract 87·5 per cent., fibre 4·8 per cent. These results show satisfactory concordance with the average of the results recorded above.

In attempting to carry out the digestibility trials with "flaked" maize as the sole source of the dietary, difficulty was at once experienced. The two White Leghorns used in the "whole" maize trial showed dislike to the food, and one of the birds had to be withdrawn from the experiment before the conclusion of the trial owing to its refusing the food. A fresh trial was therefore instituted with two Light Sussex cockerels, and the experiment was carried through to a successful conclusion. In all cases the excreta were distinctly watery. Similar difficulty was experienced with this food material in the case of pig digestibility trials carried out by Woodman (1) who finally had to include middlings with the "flaked" maize in order to bring the trials to a satisfactory conclusion. In the

case of the pig trials referred to, the trouble experienced was due to constipation owing to the high digestibility of the food in question, in our case the watery character of the faeces was due to the same cause, the amount of indigestible residue produced being relatively small compared with the large amount of watery urinary products produced.

Comparison of digestibility of "whole" maize and "flaked" maize.

In comparing the results obtained during the "whole" maize period with those obtained during the "flaked" maize period, it is necessary to consider the fact that except in one case the results were obtained with two different breeds of fowls. The close correspondence shown between the digestibility coefficients obtained with Bird 1, Light Sussex cockerel and Bird 2, White Leghorn cockerel during the "flaked" maize period indicates that there is little difference between the relative powers of digestibility of these two breeds. The average digestibility coefficients of the food nutrients of "whole" maize and "flaked" maize are as follows:

	Organic matter %	Protein %	Fat %	N-free extract %
Whole" maize	84·6	79·5	78·0	87·5
Flaked" maize	93·8	90·2	81·5	95·1

These figures show quite clearly that the process of steam cooking adopted in the commercial preparation of "flaked" maize distinctly improves the digestibility of the food nutrients of maize, and results in the production of a highly digestible product. Calculated on a dry matter basis, the amounts of digestible food nutrients in "whole" maize and "flaked" maize respectively are as follows:

Table V.

	"Whole" Maize %	"Flaked" maize %
Organic matter	83·2	93·4
Protein	8·5	9·9
Fat	4·5	1·6
N-free extract	70·2	81·9

The figures in Table V bring out very clearly that "flaked" maize contains considerably more digestible organic matter than "whole" maize, there being nearly 10 lb. more digestible nutrients in "flaked" maize in every 100 lb. dry matter as compared with "whole" maize.

Comparison of the digestibility of "whole" maize and "flaked" maize by pigs and poultry.

Records of digestibility trials with poultry and pigs have indicated that the powers of digestibility of the fowl are akin to the pig with regard to all food nutrients except crude fibre. If the digestibility coefficients for these two animals of feeding stuffs low in fibre are compared, it will be found that reasonable agreement is shown for each class of feeding stuff. Close comparison has however been found impossible owing to the fact that the experiments compared have been carried out at different institutions and on feeding stuffs of various origins. The digestibility trials carried out by Woodman in this Institute with pigs (1) on "whole" maize and "flaked" maize supplied by Messrs R. and W. Paul, Ltd., Ipswich, afforded us the unique opportunity of testing closely the relative powers of digestibility of pigs and poultry with regard to these products. The "whole" maize and "flaked" maize supplied by Messrs R. and W. Paul, Ltd., was of the same origin, the "flaked" maize being prepared in a precisely similar way, and in the same factory, as that supplied for the pig digestibility trials. For comparative purposes the relevant figures are given in Tables VI and VII below.

Table VI. *Digestibility coefficients.*

	"Whole" maize		"Flaked" maize	
	Pig (1)	Poultry	Pig (1)	Poultry
	%	%	%	%
Organic matter	87·1	84·6	95·4	93·8
Protein	78·4	79·5	95·5	90·2
Fat	63·5	78·0	44·8	81·5
N-free extract	91·5	87·5	97·1	95·1

Table VII. *Digestible nutrients of maize and "flaked" maize.*

(Calculated on basis of dry matter.)

	"Whole" maize		"Flaked" maize	
	Pig (1)	Poultry	Pig (1)	
	%	%	%	%
Organic matter	86·1	83·2	94·4	93·4
Protein	8·8	8·5	11·2	9·9
Fat	3·1	4·5	1·0	1·6
N-free extract	73·4	70·2	82·0	81·9

The figures given in Tables VI and VII strongly support the view already expressed that pigs and poultry are akin in their powers of digestibility so far as cereal products are concerned.

In the case of "flaked" maize the figures are almost identical, only the fat digestibility showing any considerable divergence.

SUMMARY.

(1) Digestibility trials with "whole" maize and "flaked" maize indicate that steam cooking by commercial processes considerably increases the digestibility of the food nutrients in maize.

(2) The view held that the fowl is akin to the pig so far as its powers of digestibility of low fibre foods are concerned is substantiated by the results of the trials here reported.

REFERENCE.

(1) WOODMAN, H. E. *J. Agric. Sci.* **15**, 1–18.

The author wishes to express his indebtedness to the Ministry of Agriculture and Fisheries and to the Poultry Industry, from whom the funds were obtained which rendered this work possible, and to record his appreciation of the services rendered by his laboratory staff, H. G. Pike, Miss N. Gass, and C. Baker.

(*Received March 3rd*, 1928.)

NITROGEN FIXATION BY SOIL MICROORGANISMS[1].

By P. G. KRISHNA[2].

(*Cornell University, Ithaca, U.S.A.*)

INTRODUCTION.

AFTER Berthelot's discovery that soil microorganisms are able to fix atmospheric nitrogen, Winogradsky isolated and demonstrated the nitrogen fixing ability of *Clostridium pasteurianum*; and later Beijerink discovered the aerobic nitrogen fixer which he termed *Azotobacter*.

Later workers had demonstrated that the activities of these microorganisms are restricted to certain ranges of the reaction of the media. *Azotobacter* is known to have an optimum range of reaction from *p*H 6·5 to 7·5, while *B. amylobacter* a range of *p*H 5·0 to 6·5. The fungi are known to be active at higher H-ion concentration.

In order to ascertain the ability and efficacy of these organisms to fix atmospheric nitrogen, media of varying reactions were inoculated with soil, and the amounts of nitrogen fixed after a certain period of incubation were determined.

METHODS.

The media used in the following experiments, with the exception of the fourth, had the following composition:

Citric acid	3·0 gm.
KH_2PO_4	5·0 ,,
$CaSO_4$	0·1 ,,
NaCl	0·2 ,,
$MgSO_4$	0·2 ,,
$Fe_2(SO_4)_3$	Trace
Dextrose	10 to 20 gm.

Distilled water to make up to 1 litre.

In the fourth experiment 5·0 gm. of citric acid and 3·0 gm. of KH_2PO_4 were used.

[1] Part of the thesis submitted to the faculty of the Graduate School at Cornell University in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

[2] The author wishes to express his indebtedness to Dr S. A. Waksman of N.J. Agric. Exp. Station, at whose suggestion this problem was taken up, and to Dr J. K. Wilson of Cornell University for criticism and encouragement.

Clark and Lub's colorimetric method for the determination of H-ion concentrations was used. The same indicators were used for titrations in adjusting the media to varying H-ion concentrations.

Bertrand's method was employed for dextrose determinations and the Kjeldahl method for the total nitrogen determinations.

EXPERIMENTAL.

The 250 c.c. Erlenmeyer flasks containing 100 c.c. of sterile media were inoculated with 0·5 gm. of soil and incubated at 25° C. for varying periods. After the incubation period the following determinations were made in all cases: the *p*H, total nitrogen and dextrose contents. In Exps. 3 and 4, 10 c.c. of the media were titrated with twentieth normal sodium hydroxide solutions with phenolphthalein as indicator, before and after the incubation periods.

In Exp. 2 a clayey soil and in Exps. 1, 2, 3 and 4 a sandy soil were used as the inoculating material. In Exp. 1, 750 mg. dextrose, in Exps. 2 and 4, 970 mg. dextrose and in Exp. 3, 2005 mg. were present in the media. As already mentioned, the media used in Exp. 4 differed from others in that it had 5 gm. of citric acid and 3 gm. of KH_2PO_4 instead of 3 and 5 gm. as in others; and besides into these was introduced a few drops of a suspension of a culture of *Azotobacter vinlandii*.

Exp. 1. Table 1[1]. *Nitrogen fixation by soil microorganisms.*

750 mg. dextrose were present in the media at the start.

	Two weeks' incubation				Three weeks' incubation			
Initial *p*H	Final *p*H	Mg. dextrose consumed	Mg. N fixed	Mg. N fixed per gm. of dextrose consumed	Final *p*H	Mg. dextrose consumed	Mg. N fixed	Mg. N fixed per gm. of dextrose consumed
3·0	3·0	90	0·15	1·5	3·0	80	0·59	7·2
4·0	4·0	110	0·15	1·4	4·0	110	0·35	3·2
5·0	4·4	680	1·57	2·3	4·2	710	1·89	2·6
5·8	4·6	700	2·29	3·3	4·4	720	2·69	3·8
6·8	4·6	670	2·29	3·4	4·6	740	2·60	3·5
7·6	7·0	690	2·54	3·7	6·8	740	2·84	3·8
8·8	4·6	690	2·43	3·5	6·8	740	2·84	3·8

All figures given in the table are averages of duplicates.

Observations made from time to time during the period of incubation indicated that in all cases there was only a scanty fungus growth below *p*H 4·8. Microscopical examination failed to show any large numbers of bacteria in the flasks whose *p*H was below 4·8. A strong

buteric acid odour, characteristic of the *B. amylobacter* group, was apparent in all flasks which had an initial reaction between *p*H 4·8 and 6·8.

Exp. 2. Table II[1]. *Nitrogen fixation by soil microorganisms.*

970 mg. dextrose were present in the media at the start.
Three weeks' incubation

Initial *p*H	Heavy clay soil: Final *p*H	Heavy clay soil: Mg. dextrose consumed	Heavy clay soil: Mg. N fixed	Heavy clay soil: Mg. N fixed per gm. of dextrose consumed	Sandy soil: Final *p*H	Sandy soil: Mg. dextrose consumed	Sandy soil: Mg. N fixed	Sandy soil: Mg. N fixed per gm. of dextrose consumed
3·0	3·4	50	0·14	2·8	3·4	110	0·72	6·5
4·0	3·8	180	0·42	2·3	3·8	175	1·28	7·3
5·8	4·2	940	2·10	2·2	4·2	930	2·26	2·4
6·2	4·6	950	3·36	3·4	4·6	950	3·10	3·2
7·0	5·0	925	2·66	2·9	5·0	940	3·10	3·3

[1] All figures given in the table are averages of duplicates.

Exp. 3. Table III[2]. *Nitrogen fixation by soil microorganisms.*

2005 mg. dextrose present at start.
Three weeks' incubation

Initial *p*H	Final *p*H	c.c. *N*/20 NaOH needed to neutralise acidity: At start	At the end	Net c.c. needed	Mg. dextrose consumed	Mg. N fixed	Mg. N fixed per gm. of dextrose consumed
3·0	3·2	7·9	7·9	0·0	95	0·28	3·0
4·0	3·8	6·3	7·1	0·8	125	0·77	6·2
5·0	4·0	5·0	13·2	8·2	1060	3·22	3·0
5·8	4·5	3·3	14·5	11·2	1435	4·41	3·0
7·2	4·6	1·1	13·4	12·3	1645	4·20	2·6
8·0	4·8	0·2 *N*/20 HCl	12·2	12·4	1705	4·90	2·9
9·4	5·0	0·95 *N*/20 HCl	12·4	13·35	1745	4·20	2·4

[2] All figures given in the table are averages of duplicates.

Microscopic examination of the bacterial mass showed an abundance of the *B. amylobacter* group and very few of other organisms. Media which had an initial reaction above 6·8 developed distinct alcoholic odour, and indications of azofication as characterised by froth and filmy growth on the surface of the media were noticeable. The microscopic examination of this filmy growth revealed it to be *Azotobacter*; considerable number of *B. amylobacter* cells were present in flasks wherein the reaction had increased on the acid side.

Exp. 4. Table IV[1]. *Nitrogen fixation by soil microorganisms.*

970 mg. dextrose present at start.

Three weeks' incubation

Initial *p*H	Final *p*H	c.c. *N*/20 NaOH needed to neutralise acidity: At start	At the end	Net c.c. needed	Mg. dextrose consumed	Mg. N fixed	Mg. N fixed per gm. of dextrose consumed
3·2	3·2	9·8	9·7	0·1	40	0·28	7·0
4·2	4·0	7·4	8·3	0·9	205	0·63	3·0
5·0	4·2	6·8	12·7	5·9	950	3·92	4·1
5·8	4·8	3·8	10·0	6·2	940	3·50	3·7
7·2	6·6	1·0	1·8	0·8	960	4·55	4·7
8·0	5·6	0·4	4·7	4·3	950	3·81	4·0
9·2	5·4	0·4 *N*/20 HCl	5·8	6·2	950	3·00	3·1

Exp. 4. Table IV (cont.)[1]. *Nitrogen fixation by soil microorganisms.*

Four weeks' incubation

3·2	3·2	9·8	9·7	0·1	50	0·28	5·6
4·2	3·4	7·4	9·3	1·9	420	0·84	2·0
5·0	4·2	6·8	11·5	4·7	970	4·06	4·2
5·8	4·6	3·8	10·2	6·4	970	3·78	3·8
7·2	7·5	1·0	0·6	−0·4	970	7·40	7·6
8·0	7·2	0·4	0·7	0·3	970	6·51	6·7
9·2	6·8	0·4 *N*/20 HCl	1·8	2·2	970	4·20	4·3

[1] All figures given in the table are averages of duplicates.

It is shown in these experiments that the fungi are responsible for the fixation of only small quantities of nitrogen. In all cases the nitrogen fixed by these organisms was below 0·84 mg.; in only one case was it 1·28 mg. These also show that *Azotobacter* and *B. amylobacter* are the important nitrogen fixing soil microorganisms.

EFFECT OF VARYING PERIODS OF INCUBATION.

It will be noted in Exps. 1 and 4 (Tables I and IV) that during the first three weeks of incubation most of the dextrose was utilised, and that during the third and the fourth weeks of incubation the organic acids and other organic products liberated into the media during the decomposition of dextrose are utilised by the *Azotobacter* group as sources of energy for nitrogen fixation. It is evident from Exp. 4 that in the media wherein the initial reaction was between *p*H 7·0 and 8·2 the nitrogen fixed in those incubated for four weeks was about 50 per cent. or more greater than in those incubated for three weeks. But the nitrogen fixed was about the same in media, the initial reactions of

which were between pH 4·8 and 6·0. That the organic acids and other products liberated into the media during the fermentation of the dextrose are utilised by the *Azotobacter* group is shown by the disappearance of these acids as measured by the titration of 10 c.c. of the media with twentieth normal sodium hydroxide. Exp. 4 shows a decrease in these acids during the fourth week as compared with the acids formed by the end of the third week. That large quantities of these organic acids are formed where there are large amounts of dextrose available is shown in Exp. 3, where 2 per cent. dextrose was used.

Effects of Varying Amounts of Dextrose.

In Exps. 1, 3 and 4 the same soil was used as the inoculant. 750 mg. in Exp. 1, 970 mg. in Exp. 4 and 2005 mg. of dextrose in Exp. 3 were used. In Exps. 1 and 4, in media where the initial reaction was 7·2 or more, the final pH did not come down as low as at other reactions. In Exp. 3 the final pH of the media, the initial reaction of which was 7·2 or more, came down to the same degree of acidity as the media at other reactions. This is clearly shown by the c.c. needed to neutralise 10 c.c. of the media. That large amounts of these acids are formed is evidenced by the fact that 12 to 14 c.c. of twentieth normal sodium hydroxide were needed to neutralise them in 10 c.c. of the media. It is also evident from Exp. 3 that these acids are not utilised in the presence of available dextrose; and also that in the presence of large amounts of dextrose large quantities of acids are formed which affect the reaction of the media which in turn may have a strong retarding effect on the growth and development of the nitrogen fixing organisms.

That the *Azotobacter* group fixes more nitrogen per gm. of dextrose consumed than the *B. amylobacter* group is indicated in all the experiments except Exp. 3. In Exp. 3 the nitrogen fixed by both groups was about the same.

The introduction of a pure culture of *Azotobacter vinlandii* in Exp. 4 did not seem to have had any bearing on the nitrogen fixation, as *Azotobacter* was present in the soil used for inoculation, except that these differences are intensified as observed by Christensen. The differences noted in Exp. 4 from those of the other experiments have already been shown to be due to the varying amounts of dextrose and the varying periods of incubation. In order to make sure that citrates were not utilised as sources of energy, *Azotobacter* was inoculated into the media free from dextrose and of an optimum reaction. No growth was observed

even after three weeks' incubation. Hence, citrates could not have been used for nitrogen fixation.

In order to determine the nitrogen fixation and the limits of activity of the *B. amylobacter* group, an attempt was made to isolate these organisms from flasks in which they were predominant. The isolated organism was not tested for purity as it was only intended to denote their activity as compared to those of the *Azotobacter* group. The bacterial mass in the culture flasks revealed no other organisms under microscopic examination. So it may be safely assumed that the nitrogen fixation noted in this experiment (Table V) must be due to this particular organism. The same media used in other experiments was used in this experiment.

It is seen from Table V that this organism is active at all reactions between *p*H 5·0 and 7·4. The optimum reaction being between *p*H 6·6 and 7·0. There is a sudden fall in the amounts of nitrogen fixed at *p*H 7·4. Only 0·91 mg. of nitrogen were fixed at *p*H 7·4, while 4·91 mg. of nitrogen were fixed at *p*H 7·0. It is also observed that this organism fixed about 4 to 5 mg. of nitrogen per gm. of dextrose consumed as compared to 10 to 12 mg. for *Azotobacter*.

The nitrogen fixing organisms seem to be equally well distributed in the heavy and light soils used in these experiments, as indicated by the amounts of nitrogen fixed at the different reactions of the media in Exp. 2.

Exp. 5. Table V[1]. *Nitrogen fixation by crude cultures of B. amylobacter.*

990 mg. dextrose present at start.

	Three weeks' incubation					
		c.c. $N/20$ NaOH needed to neutralise acidity				
Initial *p*H	Final *p*H	At start	At the end	Mg. dextrose consumed	Mg. N fixed	Mg. N fixed per gm. of dextrose consumed
3·2	3·2	11·0	11·0	0	0·07	—
4·0	4·0	8·6	8·8	0	0·14	—
5·0	5·0	6·8	6·9	15	0·14	—
5·8	5·4	4·2	6·2	612	2·03	3·32
6·6	5·0	2·7	8·8	965	3·43	3·55
7·0	5·2	1·8	7·9	975	4·91	5·14
7·4	7·0	1·0	1·5	110	0·91	8·27

[1] Figures given are averages of duplicates.

SUMMARY.

From the results presented it may be permissible to point out the following:

Fungi are responsible for the fixation of very small quantities of nitrogen, while the *Azotobacter* and *B. amylobacter* groups are the important nitrogen fixers in the soil.

B. amylobacter is able to fix from 4 to 5 mg. of nitrogen per gm. of dextrose consumed.

B. amylobacter has an optimum range of *p*H between 6·0 and 7·0, and *Azotobacter* between 7·0 and 8·4.

Azotobacter utilises the organic acids produced during the fermentation of dextrose as sources of energy for nitrogen fixation in the absence of dextrose. *B. amylobacter* does not, or does only to a limited extent, utilise such products.

Large quantities of dextrose do not favour an efficient nitrogen fixation, as large quantities of the organic acids produced effect the reaction of the media rendering the organisms inactive.

The nitrogen fixing organisms seem to be equally well represented in the heavy and light soils.

REFERENCES.

BATCHELOR, H. W. and GAINEY, P. L. (1923). *J. Agric. Res.* **24**, 757–768.

BOTTOMLEY, W. B. (1910). *Proc. Roy. Soc.* B. **82**, 622–629.

BREDEMAN, G. (1909). *Centrbl. Bakt.* 11 *abt.* V, **23**, 387.

CHRISTENSEN, H. R. (1923). *Soil Sci.* **15**, 329–360.

FRED, E. B. and DAVENPORT, A. (1918). *J. Agric. Res.* **14**, 317–336.

GAINEY, P. L. (1918). *Ibid.* **14**, 265–271.

GREEVES, J. E. (1922). *Agricultural Bacteriology.*

HUTCHINSON, C. M. (1922–23). *Agric. Res. Inst. Pusa, Science Reports.*

JOHNSON, H. W. and LIPMAN, C. B. (1922). *Calif. Univ. Pub. Agric. Sci.* **4**, 397–405.

LIPMAN, J. G. (1905). *Ann. Rept. N.J. Exp. Sta. U.S.A.*

WAKSMAN, S. A. (1927). *Principles of Soil Microbiology,* Williams and Wilkins, Co., Baltimore, U.S.A.

WINTERS, N. E. (1924). *J. Am. Soc. Agron.* **16**, 701–717.

(*Received March* 14*th*, 1928.)

THE DETERMINATION OF EXCHANGEABLE CALCIUM IN CARBONATE-FREE SOILS.

By RICE WILLIAMS, M.Sc.
(University College of North Wales, Bangor.)

The investigations carried out during the last ten years on the relationship of base exchange reactions with soil acidity have resulted in the development of new methods for the examination of soils in order to determine their need or otherwise for lime. The determination of exchangeable bases, particularly calcium, which generally forms about 80 per cent. of the total, is one of the most important of these recent developments. Of the several methods in use, the Hissink (3) method of leaching with normal sodium chloride and the Gedroiz (2) method of leaching with 0·05 *N* hydrochloric acid, applicable only to carbonate-free soils, will be discussed in connexion with work presented in the present paper. Hissink's method is generally used in this country and gives satisfactory results with soils containing no calcium carbonate. In the Gedroiz method it is assumed that in carbonate-free soils, 0·05 *N* HCl does not attack unweathered mineral particles present in the soil, and that only exchangeable calcium is brought into solution, so that the same figure for exchangeable calcium should be obtained by the two methods. This assumption may not be true for all types of soil. If unweathered minerals containing calcium are attacked by 0·05 *N* HCl, a slightly higher figure for the exchangeable calcium would be obtained than with *N* NaCl. The figures given in Table I suggest this possibility, as two of the soils show nearly the same result with both methods, whilst the other two give a definitely higher value by the Gedroiz method.

Table I. *Percentage exchangeable CaO determined by extraction with 0·05 N HCl and N NaCl.*

Soil	Hissink method	Gedroiz method
Aber I	0·186	0·190
Madryn	0·073	0·092
Aber M	0·039	0·035
X Goch	0·257	0·283

Acetic acid as a leaching agent for unsaturated soils.

The method as described by Gedroiz does not lend itself to rapidity of working, as the leachings have to be evaporated to dryness, the

organic matter destroyed, and the silica, iron and aluminium removed before the calcium is precipitated. Certain preliminary experiments suggested that dilute acetic acid might be substituted for hydrochloric acid in this method. In these experiments soil was leached with 0·2 *N* acetic acid. The calcium was precipitated as oxalate in an ammoniacal solution, after the removal of iron and aluminium, and estimated by titration with permanganate. The figures obtained are shown in Table II.

Table II. *Percentage CaO extracted from soils by* 1000 *c.c. N NaCl and* 1000 0·2 *N acetic acid.*

Soil	*N* NaCl	0·2 *N* acetic acid
C 147	0·118	0·104
A 72	0·282	0·286
C 149	0·155	0·158
C 156	0·129	0·128

The agreement shown in the preceding figures was considered sufficiently satisfactory to warrant a careful enquiry into the use of acetic acid as a leaching agent.

Precipitation of calcium oxalate.

It is well known that calcium oxalate is insoluble in acetic acid and that iron and aluminium are not precipitated from such a solution. It has been shown by an anonymous writer in *Chemical News* (1) that it can be quantitatively precipitated as oxalate from a solution of acetic acid and/or ammonium salts. It is further stated that calcium precipitated from solutions containing other metallic salts is generally obtained in a purer form in the presence of excess of acetic acid than in a neutral or slightly alkaline solution, and that the presence of ammonium salts and acetic acid effect an improvement in the filtering properties of the precipitate. It was also found that the presence of from 20 to 30 gm. of potassium or sodium chloride gave results from 1 to 3 per cent. higher than the theoretical. This last point is of importance when the exchangeable calcium is determined by the Hissink method and is confirmed by experiments carried out by the present writer (see Tables III and VI). The difference may be due to the presence of small quantities of calcium salts in the sodium chloride itself. Another point discussed in the above mentioned paper which bears on the estimation of calcium in soil extracts is the effect of magnesium on the precipitation of calcium as oxalate. It is shown that satisfactory precipitation of calcium is obtained when each 100 c.c. of solution contains not more than 0·15 gm. of magnesium oxide, by precipitation

in the presence of 10 gm. or more ammonium chloride in 2–3 per cent. acetic acid with a large excess of ammonium oxalate in the cold. Some of these statements, together with the effect of temperature of washing water on the calcium oxalate precipitate, have been tested by the present writer. The last point was suggested by the fact that the solubility curve of calcium oxalate (1) shows an increase in solubility with increase of temperature. Table III shows the results obtained in an investigation of these points.

Table III. *Effect of different media, conditions of precipitation, and washing on estimation of calcium oxide by the volumetric method.*

Theoretical amount of CaO in 100 c.c. of solution = 0·1337 gm. CaO.

Medium	Conditions of precipitation	Conditions of washing	Wt of CaO in 100 c.c.
0·5 *N* acetic acid	Hot solution	Hot water	0·1351
	—	Hot "	0·1323
	Hot solution	Cold "	0·1333
	Cold "	Hot "	0·1333
	Cold "	Cold "	0·1339
N ammonia solution	Hot solution	Hot water	0·1336
	—	—	0·1333
	—	—	0·1328
	—	Cold water	0·1333
	Cold solution	Cold "	0·1339
	Cold "	Hot "	0·1332
0·5 *N* acetic acid	Hot solution	Hot water	0·140
30 gm. NaCl	Cold "	Hot "	0·144
	Cold "	Hot "	0·143
	Hot "	Hot "	0·137

It will be observed that precipitation from a solution of pure calcium chloride in acetic acid or ammoniacal solution is complete and the temperature of washing water has no appreciable effect on the result. The presence of 30 gm. of A.R. sodium chloride in all cases gives a figure higher than the theoretical. All the above evidence, therefore, tends to show that acetic acid is a suitable medium for the exact precipitation of calcium oxalate. Having regard to the statements quoted above on the effect of ammonium salts on the filtering qualities of the precipitate, it was decided that for further work the calcium should be precipitated in an acetic acid medium partially neutralised with ammonia, or, when appreciable amounts of magnesium are present, in an acetic acid medium containing ammonium chloride.

Extraction of exchangeable calcium by varying strengths of acetic acid.

The preliminary experiments (Table II) having given such encouraging results, it was decided to test the effect of leaching with

varying strengths of acetic acid in order to determine the most convenient strength for the purpose of estimating exchangeable calcium. The figures obtained for five soils are given in Table IV.

Table IV. *Comparison of amount of CaO extracted from soils by acetic acid solutions of varying concentrations.*

Percentage of CaO extracted in first 1000 c.c. leachings.

Soil	N acid	$N/2$ acid	$N/4$ acid	$N/8$ acid	$N/16$ acid
C 147	0·104	0·103	0·105	0·100	0·093
C 149	0·152	0·150	0·147	0·152	0·149
B 04	0·164	0·158	0·156	0·154	0·153
F 11	0·226	0·222	0·232	0·206	0·190
A 72	0·278	0·278	0·273	0·273	0·243

The agreement is good and within the limits of experimental error at all the strengths except the $N/16$, where the results show a tendency to be slightly lower than the others, especially where the total exchangeable calcium oxide is high. A second litre of leachings was collected, but, with the exception of $N/16$ acid, with soils F 11 and A 72, the amount of calcium brought into solution was negligible, being less than 0·005 per cent. It seems, therefore, that any strength of acetic acid between N and $N/4$ would be equally effective in extracting the exchangeable calcium from soils. In order to be more certain that all the calcium would be leached out in the first litre, it was decided that for further work acid of 0·5 N strength should be used.

Proposed method.

The method as finally adopted may now be described in detail:

Twenty-five grams of soil ($<$ 1 mm.) are placed in a beaker with 200 c.c. of 0·5 N acetic acid solution. After stirring several times and allowing to stand for at least two hours, the supernatant liquid is poured on to a filter, the filtrate being collected in a 1000 c.c. flask. The soil is then washed on to the filter paper with 0·5 N acetic acid and leached with the acetic acid (70 to 100 c.c. at a time) until 1000 c.c. of filtrate are collected. The calcium oxide is estimated in 500 c.c. of the leachings in the following manner: 5 c.c. of concentrated ammonia (d 0·88), 10 gm. of ammonium chloride[1], and excess of ammonium oxalate solution are added and the solution vigorously stirred or boiled, and allowed to stand overnight. The precipitated calcium oxalate is then filtered, washed with water, and determined by dissolving in dilute sulphuric acid and titrating with standard potassium permanganate.

[1] When the amount of exchangeable magnesium is small, the omission of NH Cl does not appear to have any effect on the result.

The proposed method was compared with the Hissink method for a number of soils. The results are shown in Table V.

Table V. *Comparisons of amount of CaO extracted from soils by N NaCl solutions, and 0·5 N HAc solution.*

Percentage CaO extracted in first 1000 c.c. leachings.

	Soil	*N* NaCl	0·5 HAc	Diff. between NaCl and 0·5 HAc + when NaCl is greater than HAc
C 147	Light loam	0·118	0·110	+0·008
C 156	„	0·129	0·121	+0·008
C 149	„	0·155	0·150	+0·005
A 134	„	0·219	0·205	+0·014
F 11	Heavy loam	0·237	0·222	+0·015
F 43 B	Subsoil Clay	0·126	0·129	−0·003
G 72	Medium loam	0·260	0·281	−0·021
G 75	„	0·162	0·166	−0·004
A 72	„	0·282	0·278	+0·004
B 04	Light loam	0·167	0·158	+0·009
C 155	Gravelly loam	0·100	0·105	−0·005
M	Light loam	0·073	0·080	−0·007
Ab 1	Heavy loam	0·186	0·177	+0·009
XG	„	0·257	0·246	+0·011
Leeds 113	Sandy loam	0·277	0·287	−0·010
Leeds 34	Subsoil clay	0·632	0·614	+0·018
Craibstone	Light loam	0·172	0·182	−0·010
Average:		0·2088	0·2065	+0·0024

A consideration of the figures shows that, on the average, the Hissink method gives slightly higher values. However, the agreement is so close that there is good reason to assume that the calcium brought into solution by the proposed method and by the Hissink method must belong to the same category. Figures given in Table III showing the effect of addition of sodium chloride on the precipitation of calcium oxalate suggest the possibility of obtaining figures slightly in excess of the truth by the Hissink method. Confirmation of this was obtained by adding 30 gm. of A.R. sodium chloride to acetic acid leachings of soil B 04 as shown by the following figures:

	Percentage CaO	
Without NaCl	0·166 0·166	Mean 0·166
With NaCl	0·171 0·178 0·173	Mean 0·1745

This difference could be explained by the presence of very small amounts of calcium salts in the sodium chloride itself. The equivalent of 0·005 per cent. CaO (not an unreasonable amount even in A.R. material) would be reflected as 0·012 per cent. CaO in the exchangeable calcium.

Whatever the correct explanation may be, the figures given above and in Table III suggest that the Hissink method may show a slightly excessive value for the exchangeable calcium oxide. In any case the differences shown in Table V are of the order of natural variation between samples. Comparison of the two methods have been made on other soils in addition to those given in Table V. The agreement was found to be equally good except in the case of some heavy clay soils. The behaviour of these soils will now be discussed.

Heavy clay soils.

It was found that certain heavy clay soils did not give satisfactory results by the acetic acid method as described above. The figures for calcium were smaller than those obtained by the Hissink method and this was thought to be due to incomplete reaction owing to flocculation by the acid. An alternative method was therefore tried in which 10 gm. of soil were used instead of 25 gm. and the washing carried out by decantation. It will be seen from Table VI that in two of the soils this produced satisfactory results. With the third soil, however, the result was still low compared with the Hissink method. Accordingly the effect of shaking was tried. Ten grams of soil were shaken for two hours with 200 c.c. of 0·5 N acetic acid. The contents of the shaking bottle were then allowed to stand and the supernatant liquid decanted on to a filter. Further 0·5 N acetic acid was added and the bottle was again shaken for about two hours. Decantation and washing were then proceeded with until 1 litre of leachings was collected. The amount of exchangeable calcium oxide obtained shows a good agreement with the Hissink method.

Table VI. *Percentage CaO extracted from heavy clay soils.*

Soil	Percentage clay	N NaCl	0·5 N acetic proposed method	0·5 N acetic 10 gm. and decantation	0·5 acetic 10 gm. shaking and decantation
Trinidad	43	0·32	0·187	0·233	0·30
G 134 B	38	0·207	0·190	0·214	—
G 170 A	39	0·537	0·426	0·530	—

It is obvious, therefore, that although the acetic acid method is applicable to most ordinary soils, before applying it to heavy clay soils, preliminary experiments are necessary in order to ensure that an adequate extraction is obtained. It would seem that except for the heaviest of soils the use of 10 gm. of soil and washing by decantation should suffice.

SUMMARY.

(1) The possibility of using acetic acid as a reagent for extracting exchangeable calcium from carbonate-free soils is discussed, and experimental results are given showing that calcium is quantitatively precipitated from an acetic acid medium.

(2) A method for determining exchangeable calcium using 0·5 *N* acetic acid is described, and figures are given comparing this proposed method with the Hissink method.

(3) A modification of the proposed method is suggested in the case of heavy clay soils owing to the impervious nature of these soils which probably does not allow the acid to penetrate through the whole mass of the soil when leached on the filter paper.

In conclusion the writer wishes to express his thanks to Prof. G. W. Robinson, M.A., for valuable suggestions and criticisms during the course of this work.

REFERENCES.

(1) *Chemical News* (1904), **90**, 248.
(2) GEDROIZ (1923). *Soil Science*, **16**, 473–474.
(3) HISSINK, D. J. (1922). *Int. Mitt. Bodenkunde*, **12**, 104.
(4) MELLOR, J. W. *Treatise on Quantitative Inorganic Analysis*, **1**, 212.

(*Received April* 28*th*, 1928.)

VASECTOMY AS A METHOD OF STERILISING RAM LAMBS.

A COMPARISON WITH CASTRATION

By JOHN QUINLAN, M.R.C.V.S., Dr Med. Vet.
Onderstepoort Laboratory, South Africa.

(With Two Graphs and Plates III—IX.)

In a previous paper Quinlan (1) published the results of his observations on a flock of sheep which had been vasectomised for two years. The present paper contains a résumé of the data already published, to which an additional twelve months' observations have been added. This paper gives the data available from observations carried out on the flock over a period covering three years, or a period of time which allowed full skeletal development to take place.

The object in undertaking these experiments was to ascertain if there was any economic value in vasectomy over castration as a method of sterilising male lambs. At the same time an opportunity was offered to study the influence of vasectomy on the development of the secondary sexual characters of male lambs operated upon before reaching the age of three months. In any practical method of castration, of large animals at least, this question must be considered, since it is desirable that horses and cattle, which must be worked together or run together on the same farm with females of the same species, should be docile and easily managed.

The development of secondary sexual characters, of which the abeyance of sexual desire is the most important in so far as the maintenance of animals under farm conditions is concerned, is immediately checked by removal of the gonads, or by causing their atrophy by interference with the blood supply, such as is done by some methods of castration. Another secondary characteristic of male equines and bovines, which must be controlled, is the vicious tendency that is developed in many animals, so that they become a danger to their fellows or even to man. The presence of one vicious bull or one vicious stallion on a farm is most undesirable. It is not difficult to realise what a state of chaos would exist in a troop of equines behaving like stallions or a herd of bovines behaving like bulls.

In the case of sheep the development of normal sexual desire, associated with rams, would not have such a chaotic effect as in bovines or equines, provided they could be kept in a properly fenced camp. The experience gained during the progress of these experiments, however, clearly points out that it is extremely difficult to keep a group of sheep with the secondary sexual characters of rams always under control without jackal-proof camps; ordinary wire fencing is not sufficient safeguard against trespass into neighbouring camps.

It would be an advantage which must not be lost sight of in the sterilisation of male animals, if the full development of the skeleton could be maintained. It is well known that the removal of the testicles somewhat retards full skeletal development. When castrated animals reach maturity and are ready for slaughter, they cannot compare in size with males of the same species, so that in the case of bovines removal of the testicles no doubt causes a loss in beef and hide. In the case of sheep there is loss in mutton, and it requires no explanation to realise the advantage of a big-framed ram over a wether in wool production.

From a practical standpoint to the farmer in any method of sterilisation of male animals which are used as human food, the following points must necessarily be considered:

(1) Sterilisation of undesirable male animals, so that the danger of reproduction is removed.

(2) Removal of sexual desire and certain associated conditions, such as coarse and characteristically odoured flesh in bulls and rams at the time of slaughter.

(3) Removal of vicious tendency in certain male animals.

In attaining these objects the following points should be considered:

(1) Maximum growth, endurance and vitality.

(2) As a sequence to (1), maximum weight at the time of slaughter and maximum production of the most saleable variety of wool in sheep.

Prior to the present series of experiments, no consideration had been given to the possible economic value of vasectomy in the lower animals. It is doubtful if the operation was performed in South Africa prior to these experiments being undertaken.

Vasectomy has been used as a means of creating "teasers" in studs where the utmost economy is desirable with highly valuable males. Vasoligation was performed as a means of sterilisation in countries where opening of the scrotum was undesirable on account of the danger of infection with fly larvae, but was not considered as an economic possibility. The more recent methods of bloodless castration are to be preferred.

Within recent years vasectomy has been used as a means of rejuvenation in humans. Steinach (2) and Ancel and Bouin (3) maintain that ligature or section of the vasa deferentia causes an atrophy of the reproductive cells of the male gonads. As a consequence, there is an increase in the interstitial cells of the testicles, the internal secretion of which is responsible for the development of the secondary characters of the male. Steinach's experiments on rejuvenation are based on this assumption. That the physiological phenomena ascribed by Steinach to the interstitial cells in the testicles are not beyond controversy is well known. Walker (4) draws attention to the possible errors in this supposition. Some physiologists maintain that the cells of Sertoli in the tubules of the parenchyma of the gland also play an important rôle.

The Operation.

The operation of vasectomy in lambs is simple, and can be carried out expeditiously. After a little practice it is possible to vasectomise 20 to 25 lambs an hour and have 100 per cent. successful results. The most convenient time to operate is when the testicles are fairly well developed, at about two months old. It is of course possible to operate on much younger lambs without difficulty, but it appears to possess no advantage, and is considerably more difficult than at the age of two to three months. The scrotum is clipped clean of wool and the posterior surface of the sac shaved. Shaving is not absolutely necessary, but in all operations where success depends on absolute asepsis, no precaution can be considered superfluous. The lambs are prepared the day previous to the operation so that no time is lost on the day of operation.

Vasectomising lambs is extremely monotonous work, and anyone but a person extremely interested is likely after completing 100 lambs to abandon strict aseptic precautions, so that many of the subsequent operation wounds become septic, to be followed by septic periorchitis.

The lamb is placed in the dorsal position on the table and held by two assistants. The hind limbs are drawn well forward, so as to expose the scrotum as much as possible. No anaesthesia is necessary. The sac is thoroughly washed with a swab of cotton-wool, which has been moistened with ether. The hands are sterilised by first washing with soap and hot water, and then washing with corrosive sublimate and spirit solution. The instruments are used direct from the steriliser. The scrotum is taken in the left hand and one testicle drawn to the bottom of the sac, so that the cord can be easily felt towards the neck of the sac. The vas deferens is then sought for and is easily found by its characteristic cord-

like "feel." It is separated from the body of the cord by the forefinger and thumb of the left hand. The remaining fingers of the left hand are now pressed against the anterior surface of the neck of the scrotum so that the vas deferens can be felt under the skin of the posterior aspect of the scrotum. A short incision, about half an inch, is now made through the skin of the posterior aspect of the neck of the sac, parallel to its long axis, immediately over the isolated vas deferens. It is necessary to incise the tunica vaginalis as well as the skin. When the incision is complete the vas frequently protrudes from the wound. If the vas does not protrude it is picked up and withdrawn with a small blunt hook. It is then caught up in an artery forceps and about half an inch removed with the scissors. The operation is completed by putting one catgut suture in the skin wound. The second vas deferens is treated in the same way. The wounds are closed with an iodoform and collodion protective seal. In the case of very fat lambs, some difficulty will be experienced by the fat protruding through the skin wound after the incision has been completed. The fat, however, can be removed with the scissors. When the skin is sutured with catgut no after-treatment is necessary. If silk sutures are used they should be removed on the sixth or seventh day after the operation. The lambs suffer no inconvenience from the operation.

As a result of the operation there is a definite progressive change in the appearance of the testicle. For the first 12 months after vasectomy the testicle grows normally in size and shape. It is of equal weight to the testicle of a ram of the same breed, age and size. On section it is not possible to differentiate it from the testicle of a ram. There is, however, a gradual enlargement of the tail of the epididymis which at the end of 12 months reaches the size of a walnut or somewhat larger. This enlargement is due to accumulation of debris. During the succeeding 12 to 15 months the change in the appearance of the testicle is more rapid. It is possible to differentiate between a vasectomised sheep and a ram by looking at the scrotum, which shows an enlargement towards the base, due to the swollen tail of the epididymis. About two years after vasectomy the tail of the epididymis is greatly enlarged, up to about a third of the size of the testicle (Fig. 8). It forms a thin-walled fluctuating sac, which is filled with yellowish thick liquid debris. There is a distinct constriction between it and the testicle. The testicle has undergone reduction in size and has become somewhat rounded. It is softer and more flabby than the gland of a normal ram.

On section the testicle is not changed in colour, but appears unusually moist. It is yet too early to make a definite statement, but it appears

that the testicle is undergoing gradual hypoplasia. A few of the vasectomised sheep are being retained to observe the fate of the testicle.

On microscopic examination the debris taken from the tail of the epididymis is found to be composed of a structureless mass, which shows calcification in places. Occasional degenerating spermatozoa heads can be seen. The wall of the sac is composed of a very thin layer of connective tissue. The epithelial cells have undergone degeneration. In places they are entirely absent, in other places degenerated epithelial cells can still be seen.

Twelve months after vasectomy, sections of the testicle of a vasectomised sheep could not be differentiated from those of a ram (Figs. 9, 10), spermatogenesis was still quite evident, and there was no increase in the interstitial tissue. Two and a half years after vasectomy spermatogenesis was still apparent in sections from the testicles of the vasectomised sheep (Figs. 11, 12). The reproductive cells lining the tubules, however, appeared somewhat less dense than in the ram. Some of the germinal epithelial cells may have undergone disintegration. Humphrey (5) mentions that vasoligation in a goat for a period of 18 months did not produce any disturbance of spermatogenesis or hypertrophy of the interstitial cells of the testis. In a ram eight months after operation, one testicle was unchanged, while in the other the germinal epithelium was reduced and spermatogenesis was in abeyance. There was no hypertrophy of the interstitial tissue. Both the experimental animals were believed to have shown increased libido sexualis as compared with normal controls.

THE EXPERIMENT.

In September, 1923, a few sheep were vasectomised to ascertain if the expense of carrying out an experiment on a large scale would be justified. This limited experiment which was terminated after the sheep had been under observation for a period of 12 months, indicated that there were certain economic possibilities, which would justify further expense in experimental investigation.

A fairly extensive experiment was begun on the farm Bestersput, in the Free State, in October, 1924. In planning the experiment, it was decided to run the sheep under the natural veld conditions prevailing in the Free State.

The objects aimed at were as follows:

(1) To ascertain the value of vasectomy compared with castration as a practical method of sterilising male sheep.

(2) To ascertain the influence of vasectomy on the secondary male characters.

(3) To ascertain the influence of vasectomy on the skeletal development of sheep.

(4) To ascertain the influence of vasectomy on mutton production.

(5) To ascertain the influence of vasectomy on the growth and character of wool.

To obtain the best results in such an experiment, it is desirable that a purely mutton type and a purely wool type of sheep should be used. Owing to the expense entailed such an absolute division in type was not possible. The sheep were mostly selected from a mixed flock of lambs maintained on the Government farm at Bestersput. The sheep appeared to be the product of original Afrikander mothers and a merino ram. They were of the first, second and third generation. The lambs were selected from the flock at the age of two to four months. Those which showed an appearance of predominant merino were put in the wool production experiment, and those showing Afrikander predominance were selected for the mutton production experiment. The whole flock was used for observation on general and secondary sexual characters, as stated under headings 1, 2, 3 and 4.

The experiments were divided as follows:

A. Mutton type with Afrikander predominance

1. Vasectomised (37)
2. Control rams (25)
3. Control wethers (25)
4. Control ewes (40)

B. Wool type with Merino predominance

1. Vasectomised (44)
2. Control wethers (26)
3. Control ewes (30)

The experiment was begun in October, 1924. All the sheep were placed under as similar conditions as it was possible to place them on the farm Bestersput, Petrusburg District, Free State. The rams, wethers and vasectomised sheep were run together, while the ewes were run in a flock apart, but in a camp in which veld conditions differed little from that which maintained the other flock.

Each sheep was weighed at monthly intervals. They were shorn at the termination of one year, two years and three years; and observations and records made of the weight, length of staple and character of the wool. The observations were continued over a period of three years, and the details which follow in Tables I and II summarise the result.

Observations of the deaths in each flock have also been made to ascertain if any flock showed more or less resistance to natural veld conditions and diseases.

Table I. *Merino Type.*

	No. when exp. began 10. x. 24	Aver. wt. of sheep at end of 1st year lb.	Aver. increase of wt. 1st year lb.	Aver. wt. of wool 1st year lb.	Aver. length of wool 1st year in.	No. of sheep beginning of 2nd year	Aver. wt. of each sheep at end of 2nd year lb.
Ewes	30	58·5	28	5·5	2·56	29	73·9
Wethers	26	51·69	12·39	6·5	2·8	23	62·06
Vasectomised	44	65·22	27·62	5·86	2·65	36	79·8
Vasectomised (castrated)	—	—	—	—	—	—	—

	Aver. increase in wt. 2nd year lb.	Aver. wt. of wool 2nd year lb.	Aver. length of wool 2nd year in.	Aver. increase for 2 years lb.	Aver. wt. of wool in 2 years lb.	No. at beginning of 3rd year	Aver. wt. of each sheep at end of 3rd year lb.
Ewes	15·4	5·08	2·17	43·4	10·58	26	92·5
Wethers	10·37	6·18	2·2	22·76	12·68	22	97·8
Vasectomised	14·58	6·2	2·5	42·2	12·06	20*	121·0
Vasectomised (castrated)	--	—	—	--	--	10	120·95

	Aver. increase of wt. 3rd year lb.	Aver. wt. of wool 3rd year lb.	Aver. length of wool 3rd year in.	Aver. wt. of wool in 3 years lb.	Highest aver. wt. obtained lb.
Ewes	18·6	6·6	2·7	17·18	92·5
Wethers	35·74	8·6	2·63	21·28	97·8
Vasectomised	41·2	8·2	2·68	20·26	121·0
Vasectomised (castrated)	38·55	8·7	2·575	20 95	120·95

* 10 transferred to vasectomised (castrated).

It will be noticed in the graphs that there was a decrease in weight during the later winter months of each year. In consequence, the highest average weight attained in each flock is given in addition to the average weight towards the end of each year of observation.

During the winter of 1925 an unusual drought was experienced at Bestersput, and "steck gras" (*Heteropogon contortus* and *Aristida congesta*) was unusually plentiful so that the flock suffered considerably from privation. They were maintained solely on the veld, no hay or concentrates were fed. During the winter of 1926 the sheep received an additional ration of 1 lb. of lucerne hay per day. This was fed from sheep racks and was eagerly consumed. During July and August, 1927, a daily ration of $\frac{1}{2}$ lb. of "mielies" was supplied.

The flock was dosed at monthly intervals with "Government Wireworm Remedy" and always had access to a bone meal and salt lick.

Table II. *Mutton Type* (*Bastard and Bastard merino*).

	No. when exp. began 10. x. 24	Aver. wt. of sheep at end of 1st year lb.	Aver. increase of wt. 1st year lb.	Aver. wt. of wool 1st year lb.	Aver. length of wool 1st year in.	No. of sheep beginning of 2nd year	Aver. wt. of each sheep at end of 2nd year lb.
Wethers	25	64	25	5·0	2·75	23	82·2
Rams	25	60	30·5	3·19	2·25	22	80 8
Ewes	40	68	26·7	5·13	2·68	37	74·01
Vasectomised	37	72	32·0	4·62	2·5	33	77·5
Vasectomised (castrated)	—	—	—	—	—	--	--

	Aver. increase in wt. 2nd year lb.	Aver. wt. of wool 2nd year lb.	Aver. length of wool 2nd year in.	Aver. increase for 2 years lb.	Aver. wt. of wool in 2 years lb.	No. at beginning of 3rd year	Aver. wt. of each sheep at end of 3rd year lb.
Wethers	18·2	5·4	2·13	43·2	10 4	21	123 3
Rams	20·8	4·1	2·15	51·3	7·29	21	116·3
Ewes	6·01	3·44	2 08	32 71	8·57	35	95·6
Vasectomised	5·5	4·2	2 07	37·5	8 82	19*	121·7
Vasectomised (castrated)	--	—	—	-	—	10	109 85

	Aver. increase of wt. 3rd year lb.	Aver. wt. of wool 3rd year lb.	Aver. length of wool 3rd year in.	Aver. wt. of wool in 3 years lb.	Highest aver. wt. obtained lb.
Wethers	41·1	7·3	2·8	17·7	123 3
Rams	35·5	5·5	2 3	12·79	116 3
Ewes	21·59	5·2	2 5	13·77	95·6
Vasectomised	42·5	5·8	2 3	14·62	121·7
Vasectomised (castrated)	35·2	7·35	2·52	17 9	109 85

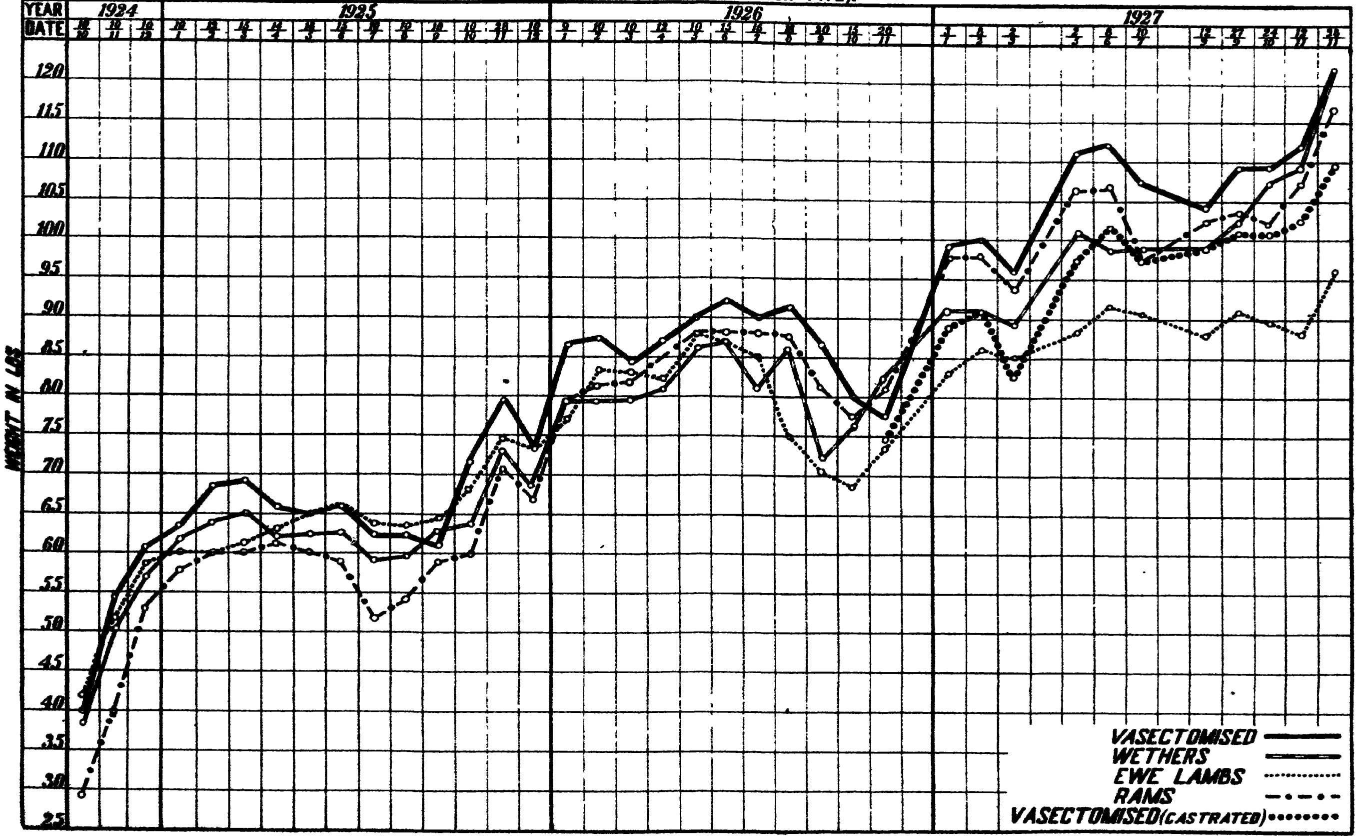
* 10 transferred to vasectomised (castrated).

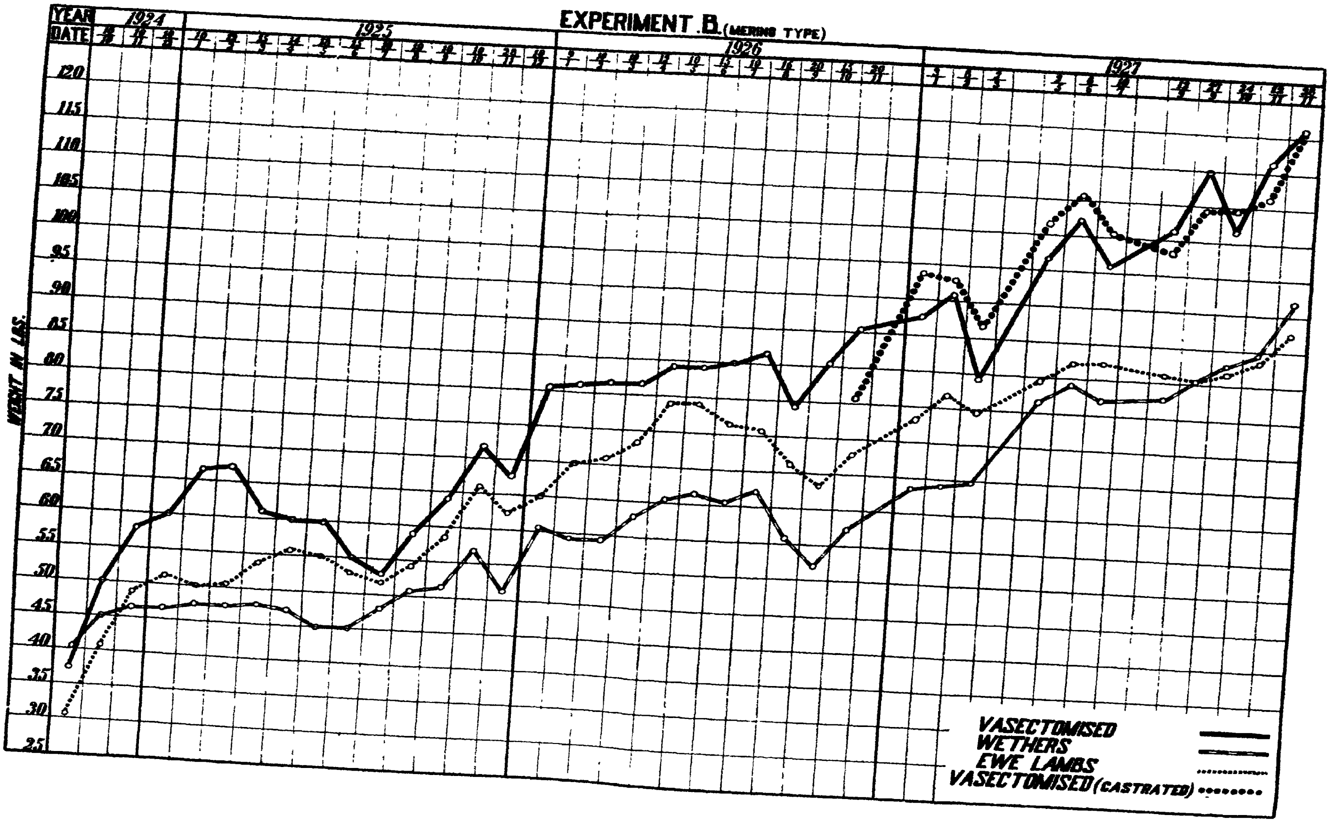
The sheep remained free from wireworm infection, but occasional post-mortems showed there was a fairly extensive *Oesophagostomum columbianum* infection.

Some of the vasectomised sheep were slaughtered to test the nature of the mutton. It was extremely good, but had a slight flavour of ram mutton.

In order to avoid any false conclusions from the tables and graphs, there are certain points which will require explanation. In the experiment B (Wool type) it will be noted that there are no control rams. This was unavoidable, since attempts made to purchase suitable ram lambs at the time were unsuccessful. The 26 wether controls were purchased from a neighbouring farm. They were practically of equal weight and a

EXPERIMENT. A. (MUTTON TYPE).





EXPERIMENT B. (MERINO TYPE)
YEAR
DATE
1924
1925
1926
1927
WEIGHT IN LBS.
VASECTOMISED
WETHERS
EWE LAMBS
VASECTOMISED (CASTRATED)

somewhat better wool type than those bred at Bestersput. This accounts for the apparent increase in wool production. Their improvement over the two years was most disappointing. This was no doubt due to a bad wireworm (*Haemonchus contortus*) and nodular worm (*Oesophagostomum columbianum*) infection before purchase, from which they failed to recover completely. The figures relating to the other groups of sheep in the experiments are reliable since they were all selected from the Bestersput flock.

During the course of the experiment the ewes maintained much better condition than the rams, wethers or vasectomised sheep. This was especially noticeable at the end of the winter. The better condition of the ewes is probably due to their docility. The rams and vasectomised sheep were very restless and considerable fighting took place daily among the flock. The wethers also maintained a more uniform covering of flesh than the rams or vasectomised sheep. They picked up condition more rapidly in the spring.

In experiment A, where the observations are confined to a mutton type of sheep with Afrikander predominance, it will be observed on consulting Table II that the vasectomised sheep were heavier at the end of the first year than the ewes, rams and wether controls. Their average weight exceeded the ewes by 4 lb., the rams by 12 lb. and the wethers by 8 lb. During the year their average increase in weight was 7 lb. more than the wethers, 1·5 lb. more than the rams, and 5·3 lb. more than the ewe controls.

It would not be of much use estimating the wool production from this type of sheep, but as the statistics as to the weight and length of staple of the wool are available they are given in the table.

At the end of the second year the average weights of the four groups of sheep in this experiment had altered. The vasectomised sheep were 4·7 lb. lighter than the wethers, 3·3 lb. lighter than the rams, and 3·5 lb. heavier than the ewes. The vasectomised sheep further showed a much lower average increase than the controls during the second year.

At the end of the second year it was decided to castrate some of the vasectomised sheep to ascertain what influence castration at 2½ years old would have now that they were fairly well grown out. Twenty were castrated with the Burdizzo pincers, 10 from the sheep in experiment A and 10 from those in experiment B. During the third year, therefore, a further group of sheep was added to each experimental flock, namely, "vasectomised (castrated)."

At the end of the third year, on completion of the experiment, the

vasectomised sheep were 1·6 lb. lighter than the wethers, 5·4 lb. heavier than the rams, 26·1 lb. heavier than the ewes and 11·85 lb. heavier than vasectomised sheep which had been castrated 12 months previously.

Owing to the circumstances already referred to, it is considered more important to give the highest average weight of the sheep in each group. The ewes and wethers kept much better condition throughout the winter, and on that account their average weights approach close to the rams and vasectomised lots towards the end of each experimental year. Had the rams and vasectomised sheep been in the same condition they would have averaged considerably more, as they were bigger of frame. The difference in condition is attributed to the restless tendency at pasture of the rams and vasectomised sheep. The 10 vasectomised sheep which were castrated did not quite keep pace with the vasectomised lot during the year.

On consulting the graph it will be seen that the vasectomised sheep maintained a higher average weight per sheep at the monthly weighings throughout the three years' observations.

The total average weight of wool produced in three years is also given in the table; but it must again be emphasised that, as the sheep in experiment A were picked for mutton rather than wool, this is of no value.

In experiment B, where the observations are confined to a wool type of sheep with merino predominance, it will be observed in consulting Table I that at the end of the first year the vasectomised sheep were 13·53 lb. heavier than the wethers and 6·72 lb. heavier than the ewe controls. They yielded an average of 0·36 lb. of wool more than the ewes, but 0·64 lb. less than the wethers. It has already been explained that the wether controls were of a better wool type, but they did not do well during the period under observation. This would account for the slightly better yield of wool, and some at least of the great difference in weight.

At the end of the second year the vasectomised sheep had not only maintained but had increased the difference in the average weight when compared with the wethers. They were 17·74 lb. heavier than the wethers and 5·9 lb. heavier than the ewes. At the end of the third year the vasectomised sheep were 28·5 lb. heavier than the ewes, 23·2 lb. heavier than the wethers, and 0·05 lb. heavier than the 10 vasectomised sheep which had been castrated.

The vasectomised lot produced an average of 20·26 lb. of wool in three years against 21·28 lb. by the wethers and 17·18 lb. by the ewe controls. Regarding the length of staple the vasectomised sheep also showed a higher average over the three years, namely, 2·6 in., against 2·54 in. by the wethers and 2·47 in. by the ewe controls.

The highest average weight during the three years is also shown by the vasectomised sheep. They reached 121 lb. which was 23·2 lb. higher than the wethers' highest average, and 28·5 lb. higher than the control ewes' highest average.

Here again it must be emphasised that the wether controls used in experiment B were a purer merino type than the ewes and vasectomised sheep. There would, therefore, be a tendency to produce more wool, which they actually did, although they did not maintain a proportional increase in body weight.

Conclusions.

1. Vasectomised sheep are sterile.
2. Vasectomised sheep, even when the operation is carried out at an early age, develop the secondary sexual characters of rams.
3. Vasectomised sheep maintain a greater weight than wethers, or ewes when fully mature, and in this respect are equal to rams.
4. The flesh of vasectomised sheep has the characteristic flavour of "ram mutton." (This can be overcome by castration six months prior to presenting for slaughter.)
5. Vasectomised sheep produce more weight of wool than wethers and ewes, and in this respect are equal to rams.
6. The quality of the wool produced is similar to that produced by rams.
7. Vasectomy appears to have little effect on the endurance and vitality of sheep when run under natural veld conditions. They were as equally susceptible to disease and climatic conditions as the controls.
8. Vasectomy has a certain economic aspect inasmuch as it allows greater skeletal development, thereby providing for more mutton and wool. When the skeletal development is attained the sheep could be castrated. (Aged sheep do not stand ordinary methods of castration without great shock. The use of the Burdizzo pincers, however, prevents this sequel.) An experiment has been carried out to test the effects of castration with Burdizzo pincers on two-year-old vasectomised sheep and rams, and it has been entirely successful.
9. The restlessness and pugnacious temperament of rams and vasectomised sheep plays a part in the putting on of flesh and the maintenance of condition. They do not appear to reach the highly fleshed condition of ewes and wethers. When kept under natural veld conditions, without an additional winter ration, they lose condition more rapidly than the placid ewes and wethers.

Fig. 1. Mutton type vasectomised sheep, taken at the end of the third year.

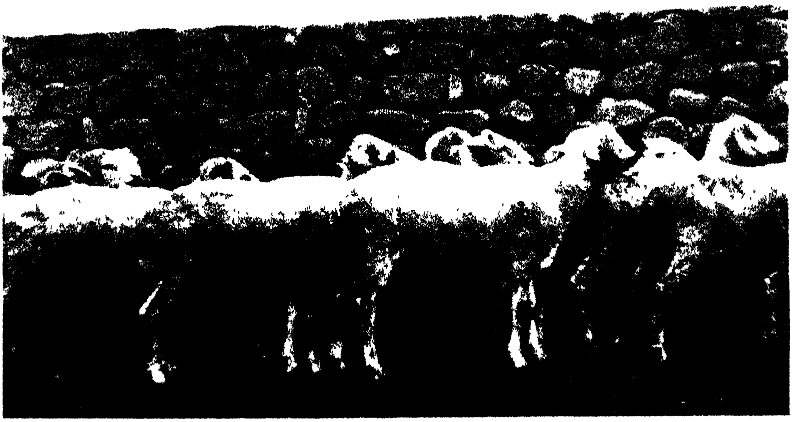


Fig. 2. Mutton type rams taken at the end of the third year.

Fig. 3. Mutton type wethers taken at the end of the third year.

Fig. 4. Mutton type ewes taken at the end of the third year.

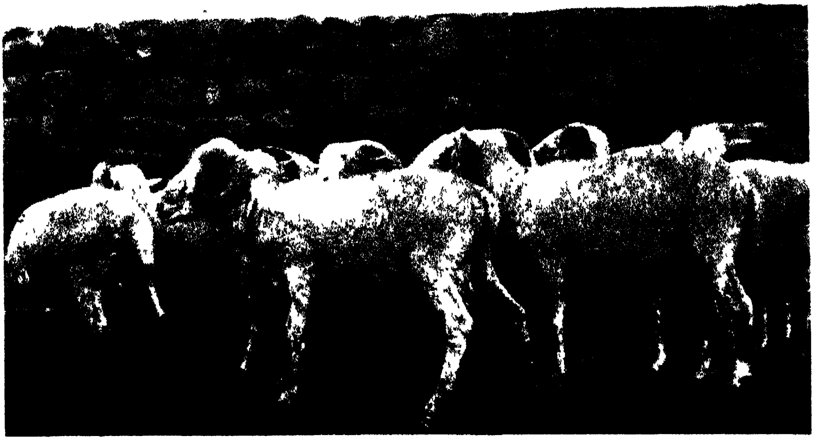


Fig. 5. Merino type vasectomised sheep taken at the end of the third year.

Fig. 6. Merino type wethers taken at the end of the third year

Fig. 7. Merino type ewes taken at the end of the third year

Fig. 8. Testicles of a vasectomised sheep (above) 2½ years after vasectomy, compared with those of a normal ram (below) of the same breed, size and age. Some of the debris in the sac formed in the epididymis is protruding through an incision in the testicle on the right.

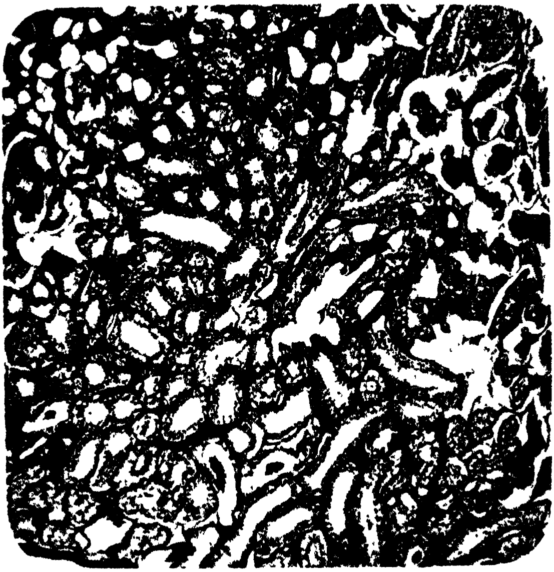


Fig. 10. Section of the testicle of a vasectomised sheep 2¾ years old, 2½ years after vasectomy. × 20.

Fig. 9. Section of the testicle of a ram 2¾ years old. × 20.

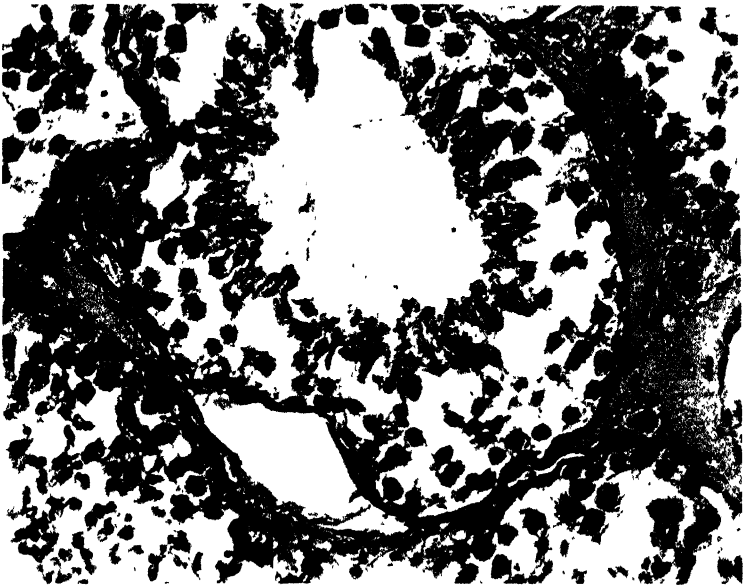


Fig. 12. Section showing the germinal epithelium from the testicle of a vasectomised sheep 2¼ years old, 2½ years after vasectomy. ×300.

Fig. 11. Section showing germinal epithelium from the testicle of a ram 2¼ years old. ×300.

10. The spermatogenesis takes place at 12 months and up to $2\frac{1}{2}$ years after vasectomy.

11. There was little or no apparent hypertrophy of the interstitial tissue in sections made 12 months and 30 months after vasectomy.

REFERENCES.

(1) QUINLAN, J. Vasectomy as a Method of Sterilising Ram Lambs. A comparison with castration. *13th Report of the Director of Veterinary Education and Research, South Africa.*

(2) STEINACH, E., cit. WALKER (1924). Feminierung von Mannchen und Maskulierung von Weibchen. *Lancet*, No. 5236, **206**, 18.

(3) ANCEL and BOUIN, cit. WALKER (1924). Recherche sur le rôle de la glande interstitielle du testicule. *Comptes rendus de l'Académie des sciences*, December, 1903. *Lancet*, No. 5236, **206**, 18.

(4) WALKER, K. M. (1924). The Internal Secretion of the Testis. *Lancet*, No. 5236, **206**, 16–21.

(5) HUMPHREY, R. R. (1926). Effects of vasoligation in sheep and goat. *Anat. Rec.* **33** (1), 41–46. Abst. from *Biological Abstracts*, **1**, No. 1, 64, December, 1926.

(*Received March 6th*, 1928.)

BORDEAUX MIXTURE IN COMBINATION WITH ARSENICAL SPRAYS.

By WM. GOODWIN and H. MARTIN.
(Research Department, South-Eastern Agricultural College, Wye, Kent.)

THE simultaneous application of a fungicide and an insecticide has become an established practice in spraying fruit trees, particularly in Canada and Australasia. The saving in time and money which is thereby effected is judged in suitable cases to compensate for certain disadvantages which are inseparable from any combined spray.

The chemical examination of a widely-used spray mixture—lime sulphur and lead arsenate—has already been made in this laboratory (1) and the investigation extended to the less commonly used lime sulphur and calcium arsenate spray (2). The effect of the addition of a "spreader" to these combined sprays has also been studied (3).

As under certain conditions the use of lime sulphur on apple trees causes a drop of young fruit, the other well-known fungicide—Bordeaux mixture—is sometimes preferred. That Bordeaux mixture can be combined with lead arsenate and other arsenicals has long been known and these mixtures have been widely used in practice. On the Continent, it would appear that Paris Green or the better standardised and more finely ground preparations known under such names as Uraniagrün, Silesiagrün, Titaniagrün, etc., are chiefly used in combination with Bordeaux mixture whilst in America calcium arsenate is replacing lead arsenate in some districts. In England, Paris Green which was formerly used to a limited extent in combination with Bordeaux mixture has entirely given way to lead arsenate.

Whilst lead arsenate paste possesses many advantages when used alone it is possible that other forms of arsenic may be as satisfactory and more economical for use with Bordeaux mixture. Thus the dry or powder form of lead arsenate and calcium arsenate both contain higher percentages of arsenic than does the paste and they give very satisfactory suspensions in Bordeaux mixture. Calcium arsenate in particular seemed to offer several advantages from the practical point of view and it was decided to include it in our enquiry.

In the chemical examination of a combined spray three main questions have to be considered: (1) has the toxic value of the fungicide

been altered? (2) is the insecticide likely to be as efficient as when used alone? (3) what effect will the mixture be likely to have on the tree or plant, especially upon the foliage? Although field trials must form the ultimate basis for recommendations with sprays, as with fertilisers, it is possible to investigate many of the properties of combined sprays in the laboratory especially with reference to the three main factors referred to above. It has been possible, for example, by a study of the lime sulphur—lead arsenate spray, to suggest that the combined spray would possess fungicidal properties superior to those of the lime sulphur alone. Biological tests have since shown that solutions of calcium polysulphide (the active constituent of lime sulphur) and of lead arsenate at concentrations below fungicidal strength proved to be fungicidal when mixed together (1). In a similar way biological tests with the hop mildew have confirmed the view that the addition of lime to dicalcium hydrogen arsenate would reduce the fungicidal power of the latter.

In dealing with Bordeaux mixture a difficulty at once arises because of the impossibility of inferring from the chemical analysis what will be the action of the mixture towards the fungus. This action, which is protective rather than direct and in this way different from that of lime sulphur, is influenced not only by the amount of copper present but also by the physical properties of the spray, *e.g.* the adhesiveness of the basic copper precipitate and the extent to which it covers the surface of the leaf and the fruit. Then too there is still great uncertainty as to the chemistry of Bordeaux mixture. It is agreed, however, that the initial reaction of lime upon a solution of copper sulphate results in a complete precipitation of copper as a basic sulphate and in the neutralisation of the natural acidity of the copper sulphate solution. If the addition of lime be continued, further reactions occur between the added lime and the copper precipitate until a point of permanent alkalinity is reached. This point occurs according to

Pickering (5)	at the molecular ratio $CuSO_4.5H_2O : Ca(OH)_2$	=	10 : 9
Sicard (6)	,, ,,	=	10 : 10
Wöber (7)	,, ,,	=	10 : 8

If the highest ratio, *i.e.* 10 : 10, be accepted it is at once obvious that when the Bordeaux mixture is made with equal weights of copper sulphate and lime, as is a common practice, the mixture contains an amount of lime far in excess of what is required to establish the "permanent" alkalinity of the spray.

The Bordeaux mixture used in the majority of the following experi-

ments was prepared to conform to the formula 8 : 8 : 100, *i.e.* 8 lb. crystalline copper sulphate and 8 lb. quicklime per 100 gallons. Hydrated lime, which is more convenient and gives a better spraying mixture, was used instead of quicklime, the formula then becoming 8 : 12 : 100 to allow for the water already combined in the calcium hydroxide. If now it be assumed that the hydrated lime contains 90 per cent. calcium hydroxide, the actual excess of calcium hydroxide present will be approximately 8·43 lb. per 100 gallons. The formula yielding a mixture of "permanent" alkalinity according to Sicard's figure would then be not 8 : 12 : 100 but 8 : 2·63 : 100. For the purposes of the work described below it was considered that the Bordeaux mixture employed consists of a suspension of unknown basic copper salts with an excess of calcium hydroxide presumably free to enter into reaction with the added arsenical compound.

The chemical factors which determine and influence the insecticidal properties of the spray are likewise but little known. It would appear from the work of Lovett (8) and Cook and McIndoo (9) that the relative stability of the arsenical as well as its content of arsenic determine its degree of toxicity. For example, the basic lead arsenates are less toxic than the diplumbic hydrogen arsenate towards the caterpillars tested not only because the former contain a lower percentage of arsenic but because a larger proportion of the material eaten passes unchanged through the intestinal tract. It is, however, doubtful whether any "availability" test determining the ease of decomposition of the arsenical compound would prove of practical value for neither the amount of poison eaten by the insect nor the amount it will void can be controlled.

In the case of factors causing foliage injury it is well established that, apart from the "russetting" injury caused by Bordeaux mixture, the arsenical injury is directly related to the concentration of soluble arsenic in the spray applied or to the amount of arsenic rendered soluble after application by such factors as leaf excretions and carbon dioxide. It is possible, however, to determine by analysis the content of soluble arsenic and to predict the likelihood of the formation of soluble arsenic after application. We have therefore been forced to confine our attention chiefly to this latter aspect of the effects of mixing lead arsenate (in paste and powder form) and calcium arsenate with Bordeaux mixture. Our plan has been to study first the action of calcium hydroxide and its derivatives upon the arsenical and then to observe the effects of the addition of copper sulphate, by which means the Bordeaux mixture was prepared.

BORDEAUX MIXTURE—LEAD ARSENATE.

An examination of the commercial lead arsenate pastes and powders used in this country has shown that the main constituent of them is the diplumbic hydrogen arsenate $PbHAsO_4$; in many cases the analyses agreed with the theoretical proportions of lead and arsenic of this compound. A certain amount of basic lead arsenate is used for spraying purposes in America but in view of its ill-defined composition and the fact that it is not in use in England, it was decided to limit the investigation in this section to the salt $PbHAsO_4$.

The first step was to study the action of calcium hydroxide upon commercial lead arsenate of the diplumbic type. This action has been investigated in America where, owing to injury being sometimes caused to peach and pear foliage when sprayed with the diplumbic arsenate, the addition of slaked lime has been recommended by the United States Department of Agriculture. The practice of adding lime to arsenical sprays such as Paris Green or London Purple to reduce the risk of foliage injury is general and it was no doubt considered that a similar reaction would occur with lead arsenate.

According to Campbell (10) the addition of lime to lead arsenate proved ineffective owing to the interaction of the lime not only with the arsenic in solution but also with the lead arsenate. Robinson (11) considered that the reaction of lime with diplumbic hydrogen arsenate could be represented by the equation:

$$3PbHAsO_4 + Ca(OH)_2 = Pb_3(AsO_4)_2 + CaHAsO_4 + 2H_2O.$$

The reaction represented by the above equation is not, however, probable as it has been shown that triplumbic ortho-arsenate does not exist as a well-defined salt and McDonnell and Graham (12) have shown that by the hydrolysis of diplumbic hydrogen arsenate the compound

$$Pb_4(PbOH)\,(AsO_4)_3.H_2O$$

is produced.

Campbell (*loc. cit.*) found, from experiments upon the disappearance of alkalinity towards phenolphthalein when small amounts of calcium hydroxide were added to suspensions of diplumbic hydrogen arsenate, that an excess of calcium hydroxide over that required by Robinson's equation was necessary. He therefore proposed the following equation to represent the reaction:

$$5PbHAsO_4 + 3Ca(OH)_2 \rightarrow Pb_4(PbOH)\,(AsO_4)_3 + Ca_3(AsO_4)_2 + 5H_2O.$$

As, after spraying, the tricalcium arsenate will decompose with the

formation of dicalcium hydrogen arsenate—a salt far more soluble than the original lead arsenate—Campbell concluded that under certain conditions the concentration of soluble arsenic may be sufficient to cause severe foliage injury.

More recently and indeed after that part of our investigation which deals with this question had been finished, Van der Meulen and Van Leeuwen (13) found that complete decomposition of part of the diplumbic hydrogen arsenate occurred by a reaction which they represented by the following equation:

$$3PbHAsO_4 + 5Ca(OH)_2 \rightarrow Ca_5(AsO_4)_3OH + 3Pb(OH)_2 + 3H_2O.$$

As, however, the reaction proceeds very slowly and requires a long-continued action of excess of lime, these workers concluded that there is less risk of foliage injury and a practical advantage in adding slaked lime to the lead arsenate spray; these conclusions were also confirmed by orchard experiments.

Finally, Ginsburg (14) dealing with the changes which take place when "Dry Mix Sulphur-Lime" and acid lead arsenate are used together investigated the effect of the addition of lime to lead arsenate. Following up the suggestion of Mogendorff (15) he concluded that if calcium carbonate is present there is an increase in the soluble arsenic and consequently a greater danger of foliage injury. He stated that "calcium carbonate in solution reacts directly with the lead arsenate, forming soluble arsenic salts."

Experimental.

The general method of experimental work was the same as that followed in our earlier investigations to which reference has been made. The decomposition of the spray mixture was effected, firstly, by drawing air from outside the laboratory through the suspension and examining samples periodically, secondly, by spraying the mixture on to glass wool and after an interval washing the glass wool with a large quantity of water and examining the filtrate for soluble constituents.

Two samples of lead arsenate were used, one a paste and the other a powder, they gave on analysis:

	Sample *A* (paste)*	Sample *B* (powder)
Moisture	39·67 %	0·84 %
Total As_2O_5 ...	19·93 %	31·77 %

* The paste had dried out somewhat before the sample was taken and therefore contains less moisture than usual.

The water-soluble arsenic, as determined by the A.O.A.C. method, was

well below 0·5 per cent.; as the figures are of little significance if below this limit they are not quoted.

Two samples of hydrated lime were used, one was old and had become partially carbonated, the analyses showed them to contain:

	Sample *A*	Sample *B*
Total $Ca(OH)_2$ ...	88·12 %	93·05 %
Total $CaCO_3$ ...	8·03 %	2·83 %

Throughout the experiments the lead arsenate was employed at a constant strength namely 0·4 per cent. for the paste and 0·2 per cent. for the powder. The strength of the hydrated lime varied, although in the majority of cases it was 1·2 per cent., which is equivalent to its concentration in the 8 : 12 : 100 Bordeaux mixture prepared from hydrated lime.

An attempt was made to determine the nature of the reaction between diplumbic hydrogen arsenate and hydrated lime by observing the formation of soluble arsenic which arose on standing in a series of mixtures of the two materials, the lime being present in increasing amounts. The idea of this was that as the ratio of lime to lead arsenate is increased the amount of lead arsenate decomposed and the amount of arsenic in solution will increase until excess of lime is present, at which point the dicalcium hydrogen arsenate that is formed will be precipitated as basic calcium arsenate. From the ratio of calcium hydroxide to diplumbic hydrogen arsenate at the point of maximum formation of soluble arsenic it should be possible to determine whether the reaction proceeds according to one or other of the following equations:

(1) Robinson (11):

$$3PbHAsO_4 + Ca(OH)_2 \rightarrow Pb_3(AsO_4)_2 + CaHAsO_4 + 2H_2O;$$

i.e. molecular ratio CaO/PbO = 1 : 3.

(2) Campbell (10) (modified):

$$5PbHAsO_4 + 2Ca(OH)_2 \rightarrow Pb_4(PbOH)(AsO_4)_3 + 2CaHAsO_4 + 3H_2O;$$

i.e. molecular ratio CaO/PbO = 1 : 2·5.

(3) Van der Meulen and Van Leeuwen (13) (modified):

$$3PbHAsO_4 + 3Ca(OH)_2 \rightarrow 3Pb(OH)_2 + 3CaHAsO_4;$$

i.e. molecular ratio CaO/PbO = 1 : 1.

Accordingly weighed amounts of the lead arsenate powder were added to a solution of calcium hydroxide diluted to permit of the complete solution of the dicalcium hydrogen arsenate formed. The mixtures were placed in tightly corked flasks, care being taken to exclude carbon

dioxide, and were left standing in a thermostat at 34° C. The flasks were shaken frequently, and in some cases after two days, and in others after seven days, the solutions were filtered off and aliquots taken for analysis. The following are certain of the results:

	Mol. ratio CaO/PbO	100 c.c. contain After 2 days gm. CaO	gm. As_2O_5	After 7 days gm. CaO	gm. As_2O_5
(1)	1 : 0	0·0284	—	0·0293	—
(2)	1 : 0·76	0·0190	0·0001	—	—
(3)	1 : 1·05	-	—	0·0177	0·0001
(4)	1 : 1·91	—	—	0·0065	0·0001
(5)	1 : 2·32	0·0034	0·0013	—	—
(6)	1 : 3·49	—	—	0·0073	0·0137
(7)	1 : 3·69	0·0061	0·0115	—	—
(8)	1 : 4·28	—	—	0·0068	0·0143
(9)	1 : 4·41	0·0072	0·0125	—	—
(10)	1 : 5·44	0·0072	0·0131	—	—
(11)	1 : 5·74	—	—	0·0064	0·0142

Two facts are at once apparent from the above table, namely, the increase in soluble arsenic and the reduction of calcium in solution. When excess of calcium hydroxide is present—as in (2), (3) and (4)—it is evident that the arsenic rendered soluble has been reprecipitated as basic calcium arsenates causing the removal of an amount of calcium from solution. Thus where, as in (5), a greater amount of lead arsenate has been decomposed more calcium has been removed than in (3). Contrary, however, to expectations the amount of calcium in solution does not rise again to its original value, which is a proof that the reactions which occur cannot be represented by any of the equations shown above. That the loss of calcium is due to the formation of basic calcium arsenates is rendered improbable by the fact that the ratio of calcium oxide to arsenic oxide in solution in (7), (8), (9), (10) and (11) corresponds (within the experimental error) to that of dicalcium hydrogen arsenate. It has been shown, however, that the solubility of dicalcium hydrogen arsenate in water at 32° C. is such that the solution contains 0·0887 gm. As_2O_5 per 100 c.c., approximately six times the maximum amount present in the above experiments.

The possibility remains that the removal of calcium from solution may be due to an adsorption process and support is given to this suggestion by the visible change in flocculation of the lead arsenate precipitate when lime water was added. An analysis of the filtered liquid immediately after the addition of an equal volume of lime water to a 0·8 per cent. suspension of lead arsenate paste (Sample *A*) showed, however,

only a slight loss in calcium content, a loss insufficient to account for the considerable deficiency noted above:

	CaO per 100 c.c.
Lime water diluted with equal volume of water	0·0608 gm.
Lime water diluted with equal volume of 0·8 % lead arsenate (*A*)	0·0565 gm.

In view of the above results it seems probable that the interaction between lime and lead arsenate cannot be represented by a simple equation such as has been proposed.

To determine the extent to which soluble arsenic is formed when the calcium hydroxide is present in considerable excess in ratios more nearly approaching those employed in practice, a further series of trials was carried out. In these experiments air was bubbled continuously through the solutions not only to secure efficient agitation but, as has been shown previously, to convert any basic calcium arsenate which might be formed into the dicalcium arsenate. This latter reaction would actually occur if the mixture were sprayed upon foliage. The suspensions were prepared to contain 0·4 per cent. lead arsenate paste (Sample *A*) and varying proportions of hydrated lime (Sample *A*).

No.		100 c.c. contain: After 3 days gm. As_2O_5	100 c.c. contain: After 9 days gm. As_2O_5	Reaction to phenol-phthalein
PL 1	0·4 % lead arsenate (*B*) alone	0·0001	0·0001	—
PL 2	„ + 0·05 % hydrated lime	0·0002	0·0123	—
PL 3	„ + 0·10 % „	0·0002	0·0107	Pink
PL 4	„ + 0·20 % „	*	0·0008	Strong red
PL 5	„ + 0·40 % „	*	0·0001	„

The most striking feature of the above results is the appearance of lead in the solutions marked with an asterisk, this point will, however, not be considered at the moment but is reserved for future discussion. In the case of PL 2 the absence of colour with phenolphthalein after nine days indicated that no calcium hydroxide was present. The arsenic present in solution approximates closely to the maximum obtained in the previous experiments and if it be assumed to be present as dicalcium hydrogen arsenate the disappearance of the lime from solution may be regarded as being due to carbonation. The alkaline reaction of PL 3, 4 and 5 is accompanied by low figures for the soluble arsenic and indicates the presence of calcium hydroxide or basic calcium arsenates. (The alkaline reaction of the basic calcium arsenates has been established (2) and is due to their hydrolysis, a reaction which also explains the readiness with which the basic calcium arsenates are converted to dicalcium hydrogen arsenate in the presence of moisture and carbon dioxide.) It

was evident that after nine days complete carbonation had not been effected in these cases.

The above experiments were therefore repeated using larger quantities of liquid and passing air through the suspensions for longer periods:

	100 c.c. solution contain gm. As_2O_5	
After	0·4 % lead arsenate (*A*) + 0·2 % hydrated lime	0·4 % lead arsenate (*A*) + 0·4 % hydrated lime
2 days	0·0002*	0·0001*
4 ,,	0·0008*	0·0001*
8 ,,	0·0011	0·0001*
12 ,,	0·0037	0·0012
16 ,,	0·0045	0·0029
20 ,,	0·0044	0·0037
26 ,,	0·0044	0·0037

In the experiments marked with an asterisk lead was present in solution; as it interfered with the estimation of the arsenic it was removed in the form of a precipitate by boiling the solution.

The results recorded in the above table again show the gradual appearance of soluble arsenic as the excess of calcium hydroxide is removed in the form of carbonate. It seems probable therefore that by some undetermined initial reaction a certain amount of the lead arsenate is decomposed giving rise to soluble arsenic which is precipitated by the excess of calcium hydroxide as basic calcium arsenates. By the action of carbon dioxide and moisture these basic calcium arsenates are changed into the relatively soluble dicalcium arsenate and calcium carbonate.

It is also significant that in the case where 0·2 per cent. hydrated lime was added the arsenic in solution after carbonation, namely 0·0044 gm. As_2O_5 per 100 c.c. is far less than that appearing in solution when only 0·05 per cent. hydrated lime was used, namely 0·0123 gm. As_2O_5 per 100 c.c. This result indicates that the initial amount of arsenic freed by the decomposition of the lead arsenate by the interaction of calcium hydroxide decreases as the concentration of calcium hydroxide is increased beyond a certain point, a conclusion similar to that reached by Campbell (10) who ascribed this "apparent contradiction to the law of mass action" to a lesser amount of hydrolysis of the diplumbic hydrogen arsenate in higher concentrations of calcium hydroxide. The hydrolysis to which he referred was that postulated by McDonnell and Graham (12):

$$5PbHAsO_4 + H_2O \rightleftharpoons Pb_4(PbOH)(AsO_4)_3 + 2H_3AsO_4.$$

The appearance of lead in solution which confirms Van der Meulen and Van Leeuwen's observation of the complete decomposition of part

of the lead arsenate would indicate a more profound reaction than this hydrolysis and the fact remains as evidence of the complexity of the changes which take place and of the inaccuracy of the preliminary assumption which formed the basis of our first experiments.

The form in which the lead is present in solution appears to be as a calcium plumbite. That the salt is not lead bicarbonate was shown from experiments recorded below in which it was found that calcium bicarbonate has little if any action upon lead arsenate and also from the fact that the lead only appears in solutions of a certain alkalinity. It is probable that the calcium plumbite is only stable in cold concentrated solutions of calcium hydroxide and experiment showed that provided the solution is not too alkaline the plumbite is decomposed on boiling.

So far we have neglected the view of Ginsburg (14) that the formation of soluble arsenic is due to calcium carbonate. Our conclusions above and in previous work have indicated that when the lime is completely carbonated it plays no further part in the reactions. Ginsburg apparently based his conclusions upon the results of the following experiments. Various suspensions were prepared, and after standing with frequent shaking for six days were filtered and the percentage present in the filtrate of the original arsenic added was determined. His results were as follows:

	Water soluble As_2O_5
Lead arsenate alone (0·3 %)	2·63 %
„ + hydrated lime (0·8 %)	0·91 %
„ + Kayso (0·1 %) ...	6·79 %

As the Kayso, a "spreader" prepared by mixing hydrated lime and casein, was found to contain calcium carbonate (derived from the hydrate of lime on exposure to the air) Ginsburg attributed the formation of soluble arsenic to the action of the calcium carbonate and was confirmed in his view by the results of a further series of experiments in which he found:

	Water soluble As_2O_5
Lead arsenate alone	2·20 %
„ + $CaCO_3$ (0·1 %) + sulphur	8·25 %

In the first series of Ginsburg's experiments the small amount of arsenic going into solution must be regarded as due to its precipitation by the large excess of calcium hydroxide, an opinion which is confirmed by Ginsburg's third series in which is shown the reduction of the arsenic rendered soluble by increasing additions of calcium hydroxide. The high result with Kayso may be ascribed to the presence of free calcium hydroxide in the comparatively small quantity of Kayso added. This

amount of calcium hydroxide is too small to ensure the precipitation of the soluble arsenic but, as we have shown, the slight excess of free lime will result in the decomposition of a relatively large amount of lead arsenate. Ginsburg's results even when using calcium carbonate itself may likewise be ascribed to the presence of free lime in the calcium carbonate used. An examination (with alcoholic phenolphthalein) of two samples of calcium carbonate, one described as "pure precipitated" and the other "A.R." (analytical reagent) showed the difficulty of securing a calcium carbonate free from minute traces of the hydroxide. Although a pink colour was slow in appearing in the case of the "A.R." sample it was definite and immediate with the "pure precipitated" sample.

An actual repetition of Ginsburg's experiments using the above two samples of calcium carbonate at a strength of 0·52 per cent. (= 0·4 per cent. calcium hydroxide) and lead arsenate powder (sample *B*) at 0·3 per cent. yielded the following results:

	Percentage of original As_2O_5 rendered soluble
Lead arsenate alone	1·0
" + $CaCO_3$ (pure precipitated) ...	10·6
" + $CaCO_3$ (A.R.)	7·4

As a decisive test, trials were carried out in the presence of carbon dioxide not only to ensure the absence of calcium hydroxide but also to ascertain whether Ginsburg's statement—"Calcium carbonate in solution reacts directly with the lead arsenate, forming soluble arsenic salts"—is correct; it was thought that possibly he was referring to calcium bicarbonate. Accordingly a mixture of lead arsenate powder (0·2 per cent.) and hydrated lime (0·4 per cent.) was placed in a "sparklet syphon," the vessel filled with water and the lime converted to carbonate and bicarbonate by the carbon dioxide liberated from the bulb. After standing two days and being repeatedly shaken the suspension was filtered, boiled to remove calcium bicarbonate, filtered and the arsenic in solution estimated:

	Percentage of original As_2O_5 rendered soluble
Lead arsenate alone	0·79
" + hydrated lime	0·67

The above figures clearly show that in the absence of calcium hydroxide there is no increase in the amount of arsenic rendered soluble by the action of calcium carbonate or calcium bicarbonate. It is significant that in none of the trials, of which the two recorded above are examples, could lead be detected in solution, thus indicating that the lead which goes into solution in the presence of excess of calcium

hydroxide (reference to which has already been made in this paper) is not present as the bicarbonate.

As soluble arsenic—which we have shown to be formed under certain conditions by the interaction of lead arsenate and hydrated lime—is a known cause of foliage injury it was important to determine the amount formed under conditions more similar to those met with in practice. For this purpose various mixtures were sprayed upon glass wool in the manner previously described (3) and at the end of certain periods the water-soluble arsenic was determined. The experiments were repeated many times to remove the possibility of the experimental error leading to wrong conclusions; the figures given in the table below may be quoted as typical:

			Gm. As_2O_5 in solution per 100 gm. spray		
			After 3 days	After 6 days	After 9 days
GPL 1	0·4 % lead arsenate (A)	... ...	0·0248	—	—
GPL 2	,,	+0·10 % hydrated lime (A)	0·0186	—	—
GPL 3	,,	+0·20 % ,,	0·0151	—	—
GPL 4	,,	+0·40 % ,,	0·0164	—	—
GPL 5	0·4 % ,,	... ...	0·0280	—	—
GPL 6	,,	+0·20 % hydrated lime (B)	0·0177	—	—
GPL 7	,,	+0·40 % ,,	0·0131	—	—
GPL 8, 9	0·2 % lead arsenate (B)	... ...	0·0151	—	0·0203
GPL 10, 11, 12	,,	+0·40 % hydrated lime (A)	0·0164	0·0167	0·0153
GPL 13, 14	0·2 % ,,	... ...	—	0·0206	0·0194
GPL 15, 16	,,	+0·40 % hydrated lime (B)	—	0·0139	0·0143

The fact that in only one case (GPL 8 and 9)[1] did the presence of hydrated lime cause an increase in soluble arsenic seems to be due either to the lime not being completely carbonated after the period of exposure or to the interaction between the lead arsenate and the hydrated lime not proceeding under these conditions at a rate sufficiently rapid to exercise an appreciable effect. The first hypothesis appears unlikely as the filtrates were never strongly alkaline and in experiments GPL 10, 11 and 12, when the sprayed glass wool was left for 3, 6 and 9 days respectively before washing through, the amounts of soluble arsenic showed no tendency to increase. The conclusion must therefore be drawn that under the conditions of the experiment the conversion of the free calcium hydroxide to calcium carbonate takes place so rapidly that the slow interaction between diplumbic hydrogen arsenate and calcium hydroxide is unable to effect any marked production of soluble arsenic.

It was observed in certain of the glass wool experiments involving the spraying with lead arsenate that the filtrate was never clear. The

[1] Even in this case the arsenic in solution for lead arsenate alone is abnormally low.

cause of the slight cloudiness, which was observed in each of the experiments recorded above, could not be traced; possibly the slight initial alkalinity of the glass wool played a part. (It was found that the water used to wash the glass wool gave a faint pink colour with phenolphthalein.) Tests made for lead in the filtrate invariably proved negative; boiling the filtrate and leaving to stand overnight as was done in experiments GPL 5, 6 and 7, slightly reduced the cloudiness yet the arsenic in solution showed no decrease. As the object of the experiments in this section was, however, to determine if an increase in soluble arsenic occurred and as an increase was not shown the cloudiness was neglected.

Ginsburg's contention that arsenic is rendered soluble by the interaction of lead arsenate and calcium carbonate was tested by similar experiments in which calcium carbonate was used instead of hydrated lime. No increase in the amount of arsenic in solution was observed as the following figures show:

	Gm. As_2O_5 in solution per 100 gm. spray
GPL 27 0·3 % lead arsenate (*B*)	0·0204
GPL 28 „ + 1 % $CaCO_3$ (A.R.)	0·0187

The Addition of Copper Sulphate to the Lead Arsenate—Calcium Hydroxide Mixture.

It was by this addition that the Bordeaux mixture—lead arsenate combined spray was prepared throughout. Very little chemical work appears to have been carried out upon this mixture. Russell (16) examined the interaction of the 2 : 1 : 10 Bordeaux mixture with a lead arsenate prepared by the precipitation of arsenate of soda with lead acetate. He recorded that it had been stated that a soluble arsenate of copper might be formed but he found that although copper entered into solution neither lead nor arsenic was present. Fields and Elliott (17) reported that the amount of arsenic found in solution is said to be very small when either acid or neutral lead arsenate is added to Bordeaux mixture. Cook and McIndoo (9), employing a dried precipitate of Bordeaux mixture, found the amount of water-soluble arsenic in the combined spray below that of the arsenical alone. The latter workers further observed that lead appeared in the filtrate but made no further comment upon this fact.

Experiments to observe the formation of soluble arsenic by the passage of air through the spray fluid were unsuccessful owing to the length of time required to ensure complete carbonation of the large

excess of calcium hydroxide present. It was, however, of interest to confirm the appearance of lead in solution and its slow precipitation as the suspension became less alkaline:

0·2 % lead arsenate (*B*) + 8 : 8 : 100* Bordeaux mixture

		*p*H (approx.)	As_2O_5 in solution	Lead in solution	Copper in solution
After 7 days	...	—	Negligible	Present	Absent
After 11 days	...	10·0	„	Slight	„
After 42 days	...	8·0	„	Absent	„

* *I.e.* a Bordeaux mixture prepared from 8 lb. crystalline copper sulphate and 8 lb. hydrated lime in 100 gallons and therefore equivalent to a 0·8 per cent. suspension.

The results of the glass wool experiments were as follows:

			Gm. As_2O_5 in solution per 100 gm. spray	
			After 3 days	After 8 days
GBP 1, 3	8 : 8 : 100	Bordeaux alone	—	—
GBP 2, 4	8 : 8 : 100	„ + 0·2 % lead arsenate (*B*)	0·0000	0·0000
GBP 5	4 : 4 : 100	„ + 0·2 % „	0·0000	—
			After 3 days	After 9 days
GBP 6, 8	8 : 4 : 100	Bordeaux alone	—	—
GBP 7, 9	8 : 4 : 100	„ + 0·2 % lead arsenate (*B*)	0·0000	0·0000
GBP 10	8 : 4 : 100	„ + 0·4 % „	0·0000	—
			After 3 days	After 8 days
GBP 11, 12	8 : 12 : 100	Bordeaux alone	—	—
GBP 13, 14	8 : 12 : 100	„ + 0·2 % lead arsenate (*B*)	0·0000	0·0000
GBP 15, 16	8 : 12 : 100	„ + 0·4 % lead arsenate (*A*)	0·0000	0·0003

The non-appearance of soluble arsenic, except in one case when the amount formed was extremely small, is remarkable. It is unfortunate however that the influence of the addition of copper sulphate upon the amount of arsenic rendered soluble cannot be contrasted in this case with the same accuracy as was possible in the calcium arsenate experiments (see later). The following experiments may be quoted as an example:

		Gm. As_2O_5 in solution per 100 gm. spray. After 3 days
GPL 10	0·2 % lead arsenate (*B*) + 0·4 % hydrated lime	0·0164
GBP 5	0·2 % „ + 0·4 % „ + 0·4 % copper sulphate	0·0000
GBP 7	0·2 % „ + 0·4 % „ + 0·8 % „	0·0000

From the above results it would appear that the addition of copper sulphate has accomplished the removal or the non-formation of soluble arsenic. The cloudiness mentioned above may be in part responsible for the highness of the figure in GPL 10; this cloudiness did not appear in the case of the combined Bordeaux mixture—lead arsenate spray.

BORDEAUX MIXTURE—CALCIUM ARSENATE.

No previous work appears to have been carried out on the chemistry of this mixture. The commercial calcium arsenates differ markedly from commercial lead arsenates in that whereas the diplumbic hydrogen arsenate is the predominant constituent of the latter, the dicalcium hydrogen arsenate is far too soluble for application to foliage. Commercial calcium arsenates are therefore prepared with a large excess of calcium and contain basic calcium arsenates together with calcium carbonate and, in some cases, calcium hydroxide.

For the purposes of this investigation, dicalcium hydrogen arsenate, prepared by the method previously described (2), was used. In addition, a basic calcium arsenate prepared by the method of Haywood and Smith (18) and two commercial calcium arsenates (Samples *B* and *C*) were used; the analysis of the various preparations yielded the following figures:

	Dicalcium hydrogen arsenate	Basic calcium arsenate	Commercial calcium arsenate *B*	Commercial calcium arsenate *C*
	%	%	%	%
Total CaO ...	28·62	39·51	40·50	44·58
Total As_2O_5 ...	58·39	39·65	43·22	43·80

The amounts of these various calcium arsenates used were regulated according to their arsenic content; the basic and commercial calcium arsenates, 0·2 per cent., dicalcium hydrogen arsenate, 0·133 per cent.

The interaction of dicalcium hydrogen arsenate and hydrated lime and the decomposition of the basic calcium arsenates have been examined in previous work (2). The results obtained indicated that the addition of lime to the calcium arsenate causes a precipitation of the soluble arsenic as more basic calcium arsenates. Upon exposure to carbon dioxide in the presence of moisture the basic calcium arsenates are converted to less basic calcium arsenates and calcium carbonate until finally the dicalcium hydrogen arsenate is formed, the excess of lime added being precipitated as calcium carbonate. The results of a series of glass wool experiments were in complete accordance with those of the previous work:

		Gm. As_2O_5 in solution per 100 gm. spray. After 3 days
GC 1	0·133 % dicalcium arsenate	0·0450
GC 2	0·133 % „ + 0·085 % hydrated lime	0·0332
GC 6	0·133 % „ + 0·8 % hydrated lime	0·0211
GC 3	0·2 % basic calcium arsenate	0·0127
GC 4	0·2 % commercial calcium arsenate (*B*)	0·0113
GC 5	0·2 % „ (*C*)	0·0089

That the arsenic is not so readily rendered soluble in the case of the basic and commercial calcium arsenates (as, for example, in GC 6 where a greater excess of free calcium hydroxide is present) is perhaps explained by their method of preparation. The calcium hydroxide in the commercial samples is more intimately mixed with the basic arsenate and is probably more protected from carbon dioxide and moisture than in the case of the freshly precipitated mixture of GC 6.

THE ADDITION OF COPPER SULPHATE TO THE CALCIUM ARSENATE—CALCIUM HYDROXIDE MIXTURE.

In view of the large excess of lime employed in the preparation of Bordeaux mixture it was thought probable that even with the relatively soluble dicalcium hydrogen arsenate the reduction of soluble arsenic would be marked. The addition of copper sulphate will, however, effect the removal of part of the free lime as calcium sulphate and perhaps in the form of additive compounds with the basic copper precipitate. It might then be thought that the Bordeaux mixture would be less effective in decreasing the amount of arsenic in solution than the hydrated lime alone. Actually in every case the addition of copper sulphate caused an enormous reduction in the amount of soluble arsenic formed, as is shown by the following results of glass wool experiments:

			Gm. As_2O_5 in solution per 100 gm. spray. After 3 days
GC 9	0·133 % dicalcium arsenate	+ 0 8 % hydrated lime	0·0193
GC 8	0·133 % ,,	+ 8 : 8 : 100* Bordeaux mixture ...	0·0001
GC 7	0·133 % ,,	+ 8 : 12 : 100 ,, ...	0·0001
GC 12	0·2 % basic calcium arsenate	+ 0·8 % hydrated lime	0·0059
GC 11	0·2 % ,,	+ 8 : 8 : 100* Bordeaux mixture ...	0·0000
GC 10	0·2 % ,,	+ 8 : 12 : 100 ,, ...	0·0000
GC 14	0·2 % commercial calcium arsenate (*B*)	+ 0·8 % hydrated lime ...	0·0039
GC 13	0·2 % ,,	+ 8 : 8 : 100* Bordeaux mixture	0·0000
GC 16	0·2 % ,, (*C*)	+ 0·8 % hydrated lime ...	0·0017
GC 15	0·2 % ,,	+ 8 : 8 : 100* Bordeaux mixture	0·0000

* Equivalent to 0·8 per cent. hydrated lime.

As in no case did the cloudiness which interfered in the lead arsenate experiments appear, it is possible to ascribe this reduction in the amount of arsenic in solution to the action of the copper sulphate. The causes of this action were not investigated for if chemical in character their elucidation would require a more definite knowledge of the chemistry of Bordeaux mixture than is at present available. It may be, however, that the action is more physical than chemical and that the deposition of the basic copper compounds upon the particles of the arsenical may

form a protective coating by which, in the case of the basic calcium arsenates, hydrolysis is retarded, or in the case of lead arsenate, the interaction with the lime is prevented. By such actions the formation of soluble arsenic is retarded and the amount of arsenic appearing in solution is materially reduced.

It has already been indicated that in the examination of the effects produced by the combination of Bordeaux mixture with arsenicals only one factor—the risk of arsenical injury—can at present be investigated in the laboratory.

It has been shown that under conditions involving the long continued action, in the presence of water, of calcium hydroxide upon lead arsenate, the latter is decomposed with the formation of basic calcium arsenates which in the presence of water and carbon dioxide are converted into the relatively soluble dicalcium hydrogen arsenate. If, however, the conditions are such that the carbonation of the excess calcium hydroxide occurs with sufficient rapidity (as for example after spraying upon the leaf) the amount of soluble arsenate compounds formed by the interaction of calcium hydroxide and lead arsenate is not sufficient to make the liability to arsenical injury greater. There are indeed indications that the addition of free lime to lead arsenate reduces the risk of arsenical injury and these indications are supported by the good results achieved in America where lime is added as a "corrective" to acid lead arsenate used on peach foliage.

In a similar manner it has been shown that lime added to dicalcium hydrogen arsenate or to basic calcium arsenates definitely reduces the risk of foliage injury. Evidence has been adduced which indicates that if instead of lime, an "equal-lime" Bordeaux mixture containing an equivalent amount of lime be used the risk of arsenical injury is markedly reduced and that such a Bordeaux mixture is far more efficient as a "corrective" than hydrated lime.

SUMMARY.

1. The interaction of Bordeaux mixture with lead arsenate and with calcium arsenate has been studied by an examination of the effects which are produced:

(*a*) When hydrated lime is added to the arsenical compounds.

(*b*) When copper sulphate is added to the arsenical compounds and hydrated lime.

2. The nature of the interaction of calcium hydroxide and diplumbic hydrogen arsenate has been shown to be most complex and to result

in the complete decomposition of part of the lead arsenate and the formation of basic calcium arsenates.

3. Support is not given to the view that calcium carbonate decomposes diplumbic hydrogen arsenate with the production of soluble arsenic compounds.

4. When the lead arsenate, in water, is allowed to interact for long periods with excess of hydrated lime, the amount of basic calcium arsenates formed is such that large quantities of arsenic are brought into solution by the action of carbon dioxide.

5. Under conditions when the calcium hydroxide is rapidly converted to the carbonate the amount of arsenic rendered soluble is slight.

6. The conclusion is formed that in actual spraying there is a definite reduction of the risk of arsenical injury when hydrated lime is added to lead arsenate and to calcium arsenate.

7. It is concluded that when the conditions are such that the addition of hydrated lime brings about a reduction of arsenical injury, the use of an "equal-lime" Bordeaux mixture containing an equivalent amount of calcium hydroxide will prove far more effective.

REFERENCES.

(1) GOODWIN, W. and MARTIN, H. (1925). *J. Agr. Sci.* **15**, 307.

(2) —— —— (1926). *J. Agr. Sci.* **16**, 596.

(3) —— —— (1925). *J. Agr. Sci.* **15**, 476.

(4) GOODWIN, W., MARTIN, H. and SALMON, E. S. (1926). *J. Agr. Sci.* **16**, 302.

(5) PICKERING, S. U. (1907). *J. Chem. Soc.* **91**, 1981.

(6) SICARD, L. (1915). *Ann. de l'École nat. d'Agr. Montpellier*, **14**, 212.

(7) WOBER, A. (1919). *Zeitsch. f. Pflanzenkrankh.* **29**, 94.

(8) LOVETT, A. L. (1920). *Oregon Agr. Exp. Sta. Bull.* **169**.

(9) COOK, F. C. and McINDOO, N. E. (1923). *U.S. Dept. Agr. Bull.* **1147**.

(10) CAMPBELL, F. L. (1926). *J. Agr. Res.* **32**, 77.

(11) ROBINSON, R. H. (1919). *J. Econ. Entom.* **12**, 429.

(12) McDONNELL, C. C. and GRAHAM, J. J. T. (1917). *J. Amer. Chem. Soc.* **29**, 1912.

(13) VAN DER MEULEN, P. A. and VAN LEEUWEN, E. R. (1927). *J. Agr. Res.* **35**, 313.

(14) GINSBURG, J. M. (1927). *J. Econ. Entom.* **20**, 625.

(15) MOGENDORFF, N. (1925). *New Jersey Agr. Exp. Stas. Bull.* **419**.

(16) RUSSELL, E. J. (1906). *J. S.E. Agr. Coll.* **15**, 93.

(17) FIELDS, W. S. and ELLIOTT, J. A. (1920). *Arkansas Agr. Exp. Sta. Bull.* **172**.

(18) HAYWOOD, J. K. and SMITH, C. M. (1918). *U.S. Dept. Agr. Bull.* **750**.

(*Received April 20th*, 1928.)

THE MECHANISM OF SECRETION OF CALCIUM AND PHOSPHORUS IN MILK.

By NORMAN CHARLES WRIGHT.

(From the National Institute for Research in Dairying, the University of Reading.)

Cary (1920) has shown that the proteins of milk are derived from the free amino-acids of the blood. He determined the amino-acid content of samples of blood obtained simultaneously from the jugular and mammary veins (representing the blood before and after passing through the mammary gland), and found that sufficient amino-acids were abstracted from the blood during its passage through the gland to account for the secretion of the whole of the milk proteins. Meigs, Blatherwick, and Cary (1919) used a similar method to determine the source of the phosphorus and the fat in milk, and showed that these two constituents have a common precursor in the phosphatide of the blood.

The secretion of the protein and the fat may be explained on the basis of the formation of these relatively indiffusible substances from their more freely diffusible precursors (*i.e.* the amino-acids and phosphatides) by the action of synthesising enzymes in the cells of the mammary gland. A mechanism of this type cannot, however, account for the secretion of the very high concentrations of phosphorus present in milk, nor can it account for the high concentrations of other ash constituents (for example, calcium and potassium), which are found in milk in quantities many times greater than they occur in blood.

The present investigation was undertaken in an attempt to elucidate the factors involved in the secretion of calcium and phosphorus in milk. These elements occur in milk in concentrations which are more than ten times those found in the blood plasma from which the milk is derived.

In a preliminary paper (Wright, 1926) it was shown that, if solutions of sodium caseinate[1] were separated from solutions containing soluble calcium salts by a membrane which permitted the free passage of salts, but which prevented the passage of caseinate molecules or ions, the calcium diffused through the membrane and accumulated in relatively high concentration on the protein side. It was suggested that this

[1] The term "caseinate" has been used throughout this paper in place of the more cumbersome "caseinogenate" of English usage. The former appears to be justified by reason of its more common use, and its convenient pronunciation.

phenomenon was due to the property of casein of forming very slightly dissociated salts with calcium, and the theory was put forward that a mechanism of this type was a controlling factor in the unequal distribution of calcium between the blood and the milk formed in the cells of the mammary gland. No attempt was made in the preliminary paper to examine in detail the physical chemistry of the systems under investigation. Further experiments have since been carried out, but with considerably improved technique. From the results obtained[1], it has been possible not only to substantiate the previous work, but to provide a quantitative explanation of the unequal distribution by a consideration of two factors; the degree of dissociation of the constituent electrolytes, and the influence of the Donnan membrane equilibrium.

A mechanism of calcium secretion based solely on the formation of undissociated calcium caseinate is, however, incapable of accounting for more than one quarter of the calcium present in the milk, since the concentration of the casein is a limiting factor in the reaction, the quantity of calcium combining with it being determined by the acidity of the solution[2].

During the progress of the previous work, certain experiments were carried out with systems containing phosphates, and it was then found that, by the interaction of calcium caseinate and sodium phosphate, a colloidal solution of calcium phosphate was formed which was itself non-diffusible across an artificial membrane of cellophane. It is the object of this paper to detail these experiments, and to show how they may be linked with the previous work to give a theory of secretion which will account satisfactorily for the high concentrations of calcium and phosphorus in milk.

EXPERIMENTAL.

(a) *The formation of colloidal calcium phosphate.*

If a solution of Na_2HPO_4 is added to a solution of $CaCl_2$, $CaHPO_4$ is formed as an insoluble flocculent precipitate which ultimately settles to the bottom of the mixed solutions, leaving a water-clear supernatant liquid. If, however, the same salt is added to a solution of Ca caseinate, or to a solution of Na caseinate to which $CaCl_2$ has been previously added, there is no precipitation of the $CaHPO_4$, but the salt is formed

[1] To be published in detail elsewhere.

[2] A 3 per cent. solution of casein at pH 6·8 will combine with approximately 0·03 per cent. of calcium. Milk contains about 0·12 per cent. of calcium, so that 75 per cent. of this must be present in some form other than the neutral caseinate.

in relatively stable colloidal solution. By further additions of $CaCl_2$ and Na_2HPO_4, more of the colloidal phosphate is formed. By this means it has been possible to prepare solutions (with 2·5 per cent. casein) having concentrations of $CaHPO_4$ as high as 0·05 N (equivalent to 0·1 per cent. calcium).

Such solutions are opaque and milky white in appearance: on dilution they appear white by reflected light and yellow-red by transmitted light. They may be kept for periods of more than six weeks in a stable condition. They have so far been prepared only between *p*H 6·5 and 7·0, but they are stable up to *p*H 8·5. If the solutions are made more alkaline by the addition of NaOH, they first lose their opacity, becoming relatively clear though slightly opalescent. But with increasing addition of alkali (beyond *p*H 9·0) they gradually form solid gels, the stability of the gel depending on the alkalinity: the greater the alkalinity, the less stable is the gel, until at *p*H 12·0 and beyond, the gel formation is only temporary, and dehydration causes a rapid formation of a precipitate of the phosphate with a water-clear supernatant liquid. These properties, though they have not been investigated in detail, give evidence that in such $CaHPO_4$ solutions we are dealing with true colloidal phenomena. It is suggestive to note that somewhat similar results are obtained on adding alkali to milk.

(*b*) *Membrane equilibria in solutions containing phosphates.*

In the previous work, the distribution of salts across a membrane of collodion or cellophane has been examined in systems containing casein, NaCl, and $CaCl_2$. Experiments have now been carried out with similar systems, but with the addition of phosphates, and in particular with the colloidal solutions of $CaHPO_4$ referred to in the previous paragraph.

Technique. Casein was prepared by the method detailed by Van Slyke (1923), which gives a product of remarkably low ash content. The dialysers used were of the type devised by Wright and Rule (1927), cellophane (0·0017 cm. thick) being employed as the membrane. This membrane is impermeable to casein, but permeable to inorganic salts. The period of dialysis in each experiment was 48 hours, this time having been found adequate for attaining equilibrium.

With regard to analysis, calcium was estimated by McCrudden's (1909) method, phosphorus by the colorimetric method of Fiske and Subbarow (1925), and chloride by a macro-method based on that of Van Slyke (1923–24). Sodium was determined throughout by difference.

Table I. *The influence of phosphate on salt distribution.*

Side I, as below.
Side II, an equal volume of distilled water.

Experiment no.	Approximate initial normalities on side I: Na caseinate (casein 2·5 %)	NaCl	$CaCl_2$	Na_2HPO_4	Normalities at equilibrium (48 hours): Calcium I	Calcium II	Sodium I	Sodium II	Phosphate I*	Phosphate II	Chloride I	Chloride II	Ratios at equilibrium: Ca_I/Ca_{II}	Na_I/Na_{II}	$\frac{Phosphate_{II}}{Phosphate_I}$	$\frac{Chloride_{II}}{Chloride_I}$
1	·0175	·050	—	—	—	—	·0395	·0282	—	—	·0220	·0282	—	1·40	—	1·28
2	·0175	—	—	·050	—	—	·0373	·0275	·0198	·0275	—	—	—	1·35	1·39	—
3	·0175	·050	—	·050	—	—	·0623	·0529	·0221	·0257	·0227	·0272	—	1·24	1·16	1·20
4	·0175	—	·050	—	·0324	·0162	·0069	·0078	—	—	·0218	·0240	2·0	0·89	—	1·10
5	·0175	—	·050	·050	·0429	·0041	·0314	·0346	·0342	·0147	·0216	·0240	10·5	0·91	0·43	1·11
6	·0175	—	·050	·040	·0419	·0054	·0246	·0290	·0272	·0104	·0218	·0240	7·7	0·85	0·38	1·10
7	·0175	—	·050	·055	·0437	·0030	·0328	·0405	·0368	·0161	·0222	·0241	11·5	0·81	0·44	1·10

* *I.e.* total phosphorus minus phosphorus of caseinogen molecule. The "total phosphorus" can be obtained by adding 0·0129 to each of these values.

Results. Typical results are shown in Table I, where the following salient features should be noted:

Experiments 1, 2, *and* 3. These experiments illustrate the equilibria in simple systems containing Na caseinate, NaCl, and Na_2HPO_4. It will be seen that the results agree approximately with Donnan's theory, assuming the caseinate to be only 65 per cent. dissociated. The greatest deviations from theoretical values appear in the phosphate ratios, but the method of analysis does not permit an accuracy greater than 0·15 in these ratios.

Experiments 4, 5, 6, *and* 7. Experiment 4 shows the result obtained with the simple system containing Na caseinate and $CaCl_2$, but no phosphate. The calcium ratio is 2·0, by no means a high ratio when compared with the succeeding experiments. It agrees with the value calculated from Donnan's theory, assuming a degree of dissociation of the Ca caseinate of 25 per cent.

If the results of this experiment are compared with the results obtained in experiments 5, 6, and 7, the very significant effect of the presence of phosphate in the systems is seen. These experiments were carried out with solutions containing Na caseinate, $CaCl_2$, and Na_2HPO_4. It has been pointed out above that in such solutions a reaction takes place which leads to the formation of $CaHPO_4$ in colloidal form. The experiments illustrate strikingly the results of such a reaction on the distribution ratios of calcium and phosphate. Both the calcium and the phosphorus are retained in very high concentration on the protein side of the membrane. With approximately equivalent concentrations of the calcium and phosphate initially present in the system, the equilibrium

ratio Ca_I/Ca_{II} is 10·5; *i.e. the presence of the casein and the colloidal phosphate has caused a retention of over 90 per cent. of the calcium on the protein side of the membrane.* Accompanying this calcium retention, there is a marked phosphate retention, amounting to between 70 and 75 per cent. of that present in the system.

By reducing the quantity of soluble phosphate in the system, the calcium ratio is reduced: by increasing the quantity of phosphate, the ratio is increased. Such a result would be expected from a consideration of the reversible reaction

$$Ca^{\cdot\cdot} + HPO_4'' \rightleftharpoons CaHPO_4 \rightleftharpoons (CaHPO_4)_n,$$

i.e. increased phosphate ions will cause an increase in the formation of the colloidal phosphate, and decreased phosphate ions will cause the reverse reaction.

It is not the object of this paper to examine in detail the physical chemistry of such systems, though the preliminary experiments indicate a promising field for investigation along such lines. The results are intended rather to demonstrate in a striking manner the enormously increased retention of calcium by casein solutions, caused by the presence of phosphates in the systems.

Discussion.

In the previous work, the part played by casein in causing the accumulation of calcium in milk from the low concentration of this element in blood has been emphasised. But a mechanism of this type has been shown to have a definite limitation in that it cannot account for more than 25 per cent. of the total calcium present in milk. The experiments in this paper indicate that a second mechanism, of a different type, may play an important part in the calcium secretion. This mechanism has its basis in the observation that, if a solution of a neutral caseinate is supersaturated with $CaHPO_4$ (by the addition of solutions containing relatively high concentrations of calcium and phosphate ions), the $CaHPO_4$ is not precipitated, but is formed as a stable colloidal solution.

The formation of the colloidal $CaHPO_4$ is dependent on two factors: first, the presence of the protein which acts as a protective agent; and second, the presence of calcium and phosphate ions in sufficiently high concentrations to exceed the solubility product of $CaHPO_4$. The presence of neutral caseinates in the milk cells is not open to doubt, so that the

first of these two conditions is fulfilled. Is there any evidence in support of the assumption that conditions also exist in these cells which will result in the necessary supersaturation with $CaHPO_4$?

By free diffusion through the cell membrane, the concentration of calcium ions in the milk cells will be at least as high[1] as in the blood plasma, *i.e.* it will be very near the point of saturation of calcium phosphate. At the same time, the breakdown of phosphatides to form fatty acids and phosphates (shown by Meigs and his co-workers to take place during milk secretion) will lead to a local accumulation of phosphate ions in the cells[2]. Conditions will therefore exist in which the concentrations of calcium and phosphate ions in the milk cells will be sufficiently high to exceed the solubility product of $CaHPO_4$. In the presence of the neutral caseinates, this salt will be formed in colloidal solution. And since colloidal $CaHPO_4$ is itself non-diffusible, it will accumulate in relatively high concentration in the cells. In this way a second mechanism will be formed for trapping calcium and phosphorus in milk.

There appear therefore to be at least two general mechanisms which may cause the accumulation of high concentrations of calcium and phosphorus in milk: first, the action of the casein, which is synthesised in the milk cells of the mammary gland from the freely diffusible amino-acids of the blood (Cary, 1920), and is capable of causing a selective absorption of calcium by the formation of the slightly dissociated calcium caseinate; and second, the process of supersaturation of this caseinate solution with $CaHPO_4$, leading to the formation of a colloidal and non-diffusible solution of this salt which is consequently trapped in the milk cells.

If a dual mechanism of this type controls the secretion of calcium and phosphorus by the cells of the mammary gland, we should expect the greater part of the calcium in milk to be present in non-diffusible form, either as caseinate or as colloidal phosphate. The following independent investigations provide evidence for this fact.

[1] It may even be slightly higher, owing to the Donnan effect of the caseinate ions present in the milk cells. In this connection it is very suggestive to note that a high concentration of casein in milk is generally accompanied by high concentrations of calcium and phosphate.

[2] The validity of this general theory of secretion is not dependent upon the correctness of the conclusions of Meigs and his co-workers, though their work provides a neat mechanism for obtaining relatively high concentrations of phosphate. The only essential to the theory is the possibility of the existence of phosphate ions in the cells in concentrations sufficiently high to cause supersaturation with $CaHPO_4$.

(*a*) Söldner, as early as 1888, drew attention to the colloidal condition of the calcium and phosphorus in milk, and an extension of his work by Van Slyke and Bosworth (1914) has shown the validity of his conclusions. By experiments in which milk was subjected to ultrafiltration, they concluded that the greater part of the calcium was present either in combination with the casein or in the form of colloidal $CaHPO_4$.

(*b*) Cranfield, Griffiths, and Ling (1927) have recently published extensive data on the analysis of nearly 700 samples of milk. They find that the average ratio of P/Ca is 0·785. The same ratio calculated for $CaHPO_4$ is 0·775, and for Ca caseinate at *p*H 6·8 is about 0·800. Cranfield's figures therefore approximate these two ratios, and provide further evidence that the greater part of the calcium in milk exists in these two forms.

(*c*) Magee and Harvey (1926) have carried out experiments on the dialysis of milk. Their results, together with those of others whom they quote, indicate that approximately 25 per cent. of the calcium is diffusible. Applied to systems of the type dealt with in this paper, in which the solution under investigation is allowed to come into equilibrium with an equal volume of water, their results indicate that a milk-water system would give a distribution ratio of the calcium of about 7·5. The experiments on the artificial systems described in this paper give ratios varying from 7·7 to 14·5, which are more than adequate to provide an explanation for the high concentration of non-diffusible calcium in milk.

The theory of secretion formulated above is not at present capable of rigid proof, nor can it give an adequate explanation of the control of the *exact* level of calcium and phosphorus in milk. It does, however, provide us with two general mechanisms which will account for the accumulation of these elements in high concentration in milk, the first essential to a more detailed investigation of exact control.

Summary.

1. The formation of colloidal $CaHPO_4$ by the interaction of $CaCl_2$ and Na_2HPO_4 in the presence of neutral caseinates has been demonstrated.

2. The colloidal $CaHPO_4$ is shown to be non-diffusible across a membrane of cellophane.

3. A theory is outlined which will account for the secretion of the high concentrations of calcium and phosphorus in milk from the low concentrations of these elements in the blood.

The work on which this paper is based was carried out in the Department of Dairy Industry of the New York State College of Agriculture, Cornell University, U.S.A., during the tenure of a Commonwealth Fund Fellowship. I wish to express my thanks to Professor J. M. Sherman for the facilities which he placed at my disposal, and to Professor P. F. Sharp for his valuable advice and criticism.

REFERENCES.

CARY (1920). *J. Biol. Chem.* **43**, 477.
CRANFIELD, GRIFFITHS, and LING (1927). *J. Agric. Sci.* **17**, 72.
FISKE and SUBBAROW (1925). *J. Biol. Chem.* **66**, 375.
MAGEE and HARVEY (1926). *Biochem. J.* **20**, 873.
MCCRUDDEN (1909). *J. Biol. Chem.* **7**, 83; **10**, 187.
MEIGS, BLATHERWICK, and CARY (1919). *J. Biol. Chem.* **37**, 1.
SÖLDNER (1888). *Landw. Vers.-Sta.* **35**, 351.
VAN SLYKE (1923). *Proc. World's Dairy Congress*, **2**, 1145.
—— (1923–24). *J. Biol. Chem.* **58**, 523.
VAN SLYKE and BOSWORTH (1914). *N.Y. Agric. Exp. Sta. Tech. Bull.* **39**.
WRIGHT (1926). *J. Agric. Sci.* **16**, 640.
WRIGHT and RULE (1927). *J. Biol. Chem.* **75**, 185.

(*Received April 14th*, 1928.)

THE SCIENTIFIC BASIS OF RATIONING ANIMALS.

By Professor T. B. WOOD, C.B.E., F.R.S. and
J. W. CAPSTICK, O.B.E., M.A., D.Sc.
(*Animal Nutrition Institute, School of Agriculture, Cambridge.*)

Four years ago one of us (1) propounded a method of computing rations for all classes of farm animals on the basis of a maintenance ration related to the animal's live-weight plus a production ration estimated in accordance with the amount and kind of product—such as live-weight increase, work, milk—which the animal is expected to produce. This method is on the same lines as the modern method of computing rations for milch cows which is based on Kellner's work (2). It has been used in practice for the last four years and has been found to be successful, not only as a practical method of computing rations, but more especially as a logical and intelligible method of teaching students. For this latter purpose it is a great advance over the learning of standard rations since it appeals rather to the reasoning powers than to the memory. In view of these considerations, the method has been incorporated in *Rations for Live-stock* (3). Much of the time of the Staff of the Cambridge Animal Nutrition Institute has been devoted, during the last four years, to investigations designed to fill the gaps in our knowledge of the basal metabolism, the maintenance requirement, and the production requirement of farm animals.

Up to the present no general statement of the fundamental considerations on which the method is based has been published. The following pages attempt to supply this deficiency and to justify, by collecting together the results which have been already achieved by its use, the general applicability of the method, and the possibility of extending its utility in many directions.

In the first place it should be clearly stated that the method was made possible by Kellner's conception of net nutritive value—starch equivalent—and by the further development of this idea by Armsby under the name "net energy." From Kellner's tables of starch equivalents (4) and Armsby's tables of net energy (5), it is possible to compute the net nutritive value, either in lb. starch equivalent or in Calories of net energy, of a weighed ration consisting of feeding stuffs included in the above tables.

Secondly, it has been abundantly demonstrated by Animal Calorimetry (6) that the law of the conservation of energy holds in the nutrition of animals. It follows, therefore, that the net energy of any given ration must be equal to the energy used in basal metabolism, plus the energy used in muscular movement, plus the energy used or stored in any form of production in which the animal consuming the given ration is concerned.

In the case of an animal producing milk or work at the expense of its own tissues through underfeeding, the net energy resulting from the loss of tissue constituents must be added to the net energy of the ration, or alternatively, it must appear on the other side of the equation prefixed with a minus sign. In other words, the net energy of the ration consumed by an animal must provide:

(1) The net energy for its basal metabolism.

(2) The net energy for normal muscular movement, *e.g.* getting up, lying down, standing, searching for food.

(3) The excess of net energy over the sum of (1) and (2) which is available for production of work, milk, or growth.

(4) If the sum of (1) and (2) is equal to or exceeds the net energy of the ration, then if work or milk is produced, tissue constituents must be used for the purpose. The animal will lose weight and the energy value of this loss must be added to the rations.

In order to make the argument as simple as possible, let us limit ourselves in the first place to the case of an animal, say a wether sheep six months old, where we have to take account only of the requirements for maintenance and live-weight increase. If we write an equation for computing the ration of such an animal, there will appear on the left hand side of the equation the ration R, per unit time—the usual unit for sheep is the week—expressed in terms of net energy, either starch equivalent or Calories. On the other side of the equation there must be two terms, one expressing the net energy required for maintenance, the other the net energy stored as increased live-weight. There is in general no difficulty in expressing the ration R in terms of net energy. The starch equivalent content of the separate constituents can be found from Kellner's tables (7), or the net Calories from Armsby's tables (8). The second term on the other side also presents no difficulty. It consists of two factors, the live-weight increase, g, in lb. per unit time—per week in the case of the sheep—and the quantity of net energy c as lb. of starch equivalent,

or Calories of net energy required to make an increase of 1 lb. The term will therefore be gc.

The first term is however not quite so simple. Strictly, it should be divided into two terms. One is the basal metabolism which is proportional to the surface area of the animal, and is a measure of the net energy required to carry on the vital functions of the resting and fasting animal. This part can be expressed as Ab, where A is the surface area of the animal and b the basal metabolism per unit time. For animals geometrically similar in shape, the surface area is proportional to the live-weight raised to the two-thirds power, or in other words, to the square of the cube root of the weight, and can be expressed as $kw^{\frac{2}{3}}$ where w is the live-weight, and k is a constant for any class of animal. The term may therefore be written $kw^{\frac{2}{3}}b$.

The second part of the maintenance term is the net energy used in normal daily movements. This is probably proportional, or approximately proportional, to the live-weight, but before it can be used as a separate term, some measurable quantity must be found which can be taken as proportional to the amount of movement. If such a quantity, say q, could be found, then this term could be written qwe, where e is the quantity of energy corresponding to unit value of qw, w being the live-weight.

We are engaged in experiments which may enable us to find a method of measuring q, but for the present nothing better can be done than to combine the two parts—basal metabolism and energy value of average normal movements—together in a single expression, and, since basal metabolism is almost invariably greater than the energy value of average daily movement, take the whole term as being proportional to surface area. This is theoretically incorrect but it is not likely to lead to considerable error as the energy value of average normal movement is small compared with basal metabolism. The sum of the two quantitites represents a perfectly well known figure—the maintenance requirement—which is the amount of net energy required to prevent the animal from losing or gaining live-weight. All writers have treated the maintenance requirement as proportional to surface. The above considerations show that treatment in this manner involves a small error, which however cannot at present be avoided.

If now we call m the maintenance requirement per square metre per unit time we can write our equation thus:

$$R = Am + gc.$$

If m and c are known, this equation at once makes it possible to compute

the ration required to produce any desired rate of live-weight increase which is within the capacity of the animal.

The following instance (9) shows that rations computed on this basis produce in fact the rate of increase which they are designed to achieve. During the years 1924–1926 about 500 sheep were fattened on a farm in Norfolk. Their average live-weight was 110 lbs. which corresponds to a maintenance requirement (Am.) of 9·3 lbs. starch equivalent per week. In 1924 typical animals were slaughtered at the beginning and end of the fattening period. Their carcases were analysed and the composition of their increase in live-weight computed. It was found that 1 lb. live-weight increase contained 2638 Calories, which corresponds to

$$2638 \div 1070 = 2{\cdot}47 \text{ lb. of starch equivalent.}$$

Such sheep are able if properly fed and managed to increase at the rate of 2 to 3 lb. per head per week. They were given a ration containing 14·8 lb. of starch equivalent per head per week which was computed to produce about $2\frac{1}{4}$ lbs. of live-weight increase per head per week, thus:

$$R = Am + gc.$$
$$14{\cdot}8 = 9{\cdot}3 + 2{\cdot}47g.$$
$$g = 2{\cdot}23.$$

The actual average live-weight obtained during the three seasons was 2·22 lb. per head per week.

But the same equation may be used to solve a variety of other problems. Suppose for instance that R is accurately known, but m and c are unknown. Then if we have two equations which can be solved as ordinary simultaneous equations, it is possible to find the values of m and c.

Here however it is necessary to insert a word of warning. It would be quite useless for instance to measure R, Am and g for the same animal for two successive days or weeks and to construct equations from these measurements. The two equations would be so nearly identical that the ordinary procedure for eliminating one unknown would result in eliminating both. The same result would also follow if R, Am and g were measured for two similar animals similarly fed and managed.

In any case, so few as two equations would give a very poor or even an absurd result, because it is not possible to determine the live-weight of an animal with sufficient accuracy. The only practicable method is to spread the experiment over as long a period as possible so as to minimise the errors of the weighings as compared with the other measurements, to use a large number of animals varying considerably in live-weight and

fed on varying rations, to write an equation from the figures corresponding to each animal and to extract the best values for the unknowns by the method of least squares. This method was used successfully by the writers to find the maintenance requirement of adult sheep(10). The method of solving the equations is explained in the paper mentioned. Stated briefly it is as follows.

Multiply each of the equations throughout by the coefficient of m in that equation and add all the resulting equations together. This gives a new equation which may be written

$$\Sigma AR = m\Sigma A^2 + c\Sigma Ag.$$

Next carry out a similar process by multiplying each equation by its coefficient of c and adding. We get thus a second equation

$$\Sigma gR = m\Sigma Ag + c\Sigma g^2.$$

If these two composite equations are now solved in the usual way for the unknowns m and c we shall get the best values that the material is capable of giving.

Digestibility determinations carried out on sheep by Dr H. E. Woodman provided the measurements of rations, live-weights and live-weight increases which made it possible to write twenty-eight separate equations of the form $R = Am + gc$. The rations were in all cases near maintenance level. In fourteen cases there was a gain in live-weight, in the other fourteen a loss. Two solutions were made by the least square method, one for those which gained weight, one for those which lost weight as it could not be assumed that c is the same for the gainers and the losers.

The two values found for m were 1·07 and 1·13, with a mean of 1·1 lb. of starch equivalent per square metre per day. This mean value corresponds to a maintenance requirement of 1·26 lb. of starch equivalent per day, or 8·82 lb. of starch equivalent per week, for an adult sheep weighing 100 lb. live-weight. This figure adjusted to the two-thirds power of the live-weight has been applied to a number of feeding trials and found in every case to give reasonable results.

The digestibility determinations quoted above provided excellent material for the calculation of m because the ration in each case being near maintenance level, live-weight changes were small. Consequently the m term was large in comparison with the c term. The c term was in fact only in the nature of a small correction.

To compute reliable values for c, the equations should be based on live-weight increase measurements of large numbers of animals consuming a full ration on which they make a large live-weight increase. The following figures quoted from an experiment (11) by one of us illustrates this point.

For the first three months of the winter of 1925, fifty sheep of average live-weight 101 lb., whence $Am = 8{\cdot}9$ lb. S.E. per head per week, were given a ration containing 14·0 lb. of starch equivalent per week. Their average weekly gain in live-weight was 2·40 lb. From these figures c is found thus:

$$\begin{aligned} R &= Am + gc. \\ 14 &= 8{\cdot}9 + 2{\cdot}4c. \\ 2{\cdot}4c &= 5{\cdot}1. \\ c &= 2{\cdot}13 \text{ lb. S.E. per lb. increase.} \end{aligned}$$

For the last month of the same winter, 150 sheep of average live-weight at this date 127 lb., whence $Am = 10{\cdot}3$ lb. S.E. per head per week, were given a ration containing 16·2 lb. of S.E. per head per week. Their average weekly gain in live-weight was 2·19 lb. From these figures c is found thus:

$$\begin{aligned} R &= Am + gc. \\ 16{\cdot}2 &= 10{\cdot}3 + 2{\cdot}19c. \\ 2{\cdot}19c &= 5{\cdot}9. \\ c &= 2{\cdot}70 \text{ lb. S.E. per lb. increase.} \end{aligned}$$

It is noteworthy that in each case the c term was fairly large and that the value of c is higher in the later stages of feeding, as the gains of weight then contain a greater proportion of fat.

The equation $R = Am + gc$ has still another use. It serves to calculate from the results of suitably conducted feeding trials the net energy or starch equivalent of any feeding stuff which can form a considerable proportion of the total ration. In this case the equation takes the form $r + px = Am + gc$, where r is the no. of lb. of starch equivalent in the known constituents of the ration, p the no. of lb. of the feeding stuff of unknown starch equivalent included in the ration, and x the starch equivalent per 100 lb. of the feeding stuff whose net nutritive value it is desired to determine. Then if r, p, m and g and c are known, x can readily be calculated. The following cases, quoted from a paper (12) by one of us, illustrates this method.

Starch Equivalent of Norfolk Swedes.

Average live-weight of 50 sheep under experiment =102 lb., whence Am = 8·9 lb. S.E. per head per week.

Average ration per week during experiment:
Norfolk Swedes 145 lb. = $1{\cdot}45x$ lb. S.E. if x = S.E. in 100 lb. of Norfolk swedes.
Hay, cake and barley 5·7 lb. S.E.
Therefore $R = 5{\cdot}7 + 1{\cdot}45x$ lb. S.E. per head per week.
Estimated value of c during period of experiment 2·15 lb. S.E.
Average weekly gain, g, during period = 2·45 lb.

Then
$$R = Am + gc.$$
$$5{\cdot}7 + 1{\cdot}45x = 8{\cdot}9 + 2{\cdot}45 \times 2{\cdot}15.$$
$$1{\cdot}45x = 8{\cdot}47.$$
$$x = 5{\cdot}84 \text{ lb. S.E. per 100 lb. swedes.}$$

It will be noted that the swedes supplied considerably more than half the total starch equivalent of the ration. If the method is used for feeding stuffs forming a small proportion of the ration it will be at the expense of accuracy.

Deighton's investigations (13) of the basal metabolism of the growing pig have shown that the basal metabolism, and consequently the maintenance requirement per square metre of surface, of this animal are not constant throughout life. In the case of the large white pig which Deighton studied, the basal metabolism per square metre per hour at weaning was 56 Calories. From this point it rose to 72 Calories at 4 months, its maximum value, falling slowly to 43 Calories at 12 months. Taken in conjunction with du Bois' figures (14) for the basal metabolism of the human child, this suggests that the practice of calculating the maintenance requirement of young animals by applying the surface law (two-thirds power of the live-weight) to the maintenance requirement of adult animals is not reliable. Practically all maintenance requirement experiments have been made in adult animals, and calculated from these experiments by the surface law. It is important therefore to check existing figures for the maintenance requirements of young animals. The equation $R = Am + gc$ makes such checks possible, though there is little experimental material available at present.

So far we have dealt only with a simple case where production is limited to increase in live-weight. But other forms of production, *e.g.* work and milk, are equally important. About work we are at present

unable to make any statement for the reasons already stated, namely, that we have not yet succeeded in devising a simple method of recording the quantity of movement. We have been compelled therefore to fall back upon the scientifically undesirable expedient of assuming that average daily movement remains fairly constant and can be included in the maintenance requirement. We have not yet attempted to measure or record movements which would be classed as work from the point of view of work production.

Extension of the equation so as to include milk production is however quite simple. If the volume of milk yielded per day is v gallons, and weight of starch equivalent required to make 1 gallon of milk l lbs., then the equation for milk production will be:

$$R = Am + gc + vl.$$

Kellner (15), as the result of a complete balance experiment on three cows, in which he estimated from the carbon and nitrogen balance how much of the ration after subtraction of the maintenance requirement was used for production of live-weight increase and how much for production of milk, concluded that 1 lb. of starch equivalent produced a quantity of milk which contained 1350 Calories approximately. Normal average milk contains approximately 3000 Calories per gallon. Therefore 1 gallon of milk requires for its production 3000 ÷ 1350, or 2·2 lbs. of starch equivalent.

Modern milk rationing as nowadays so widely and successfully practised has been built up on this figure, though the officially accepted figure (16) for the production of 1 gallon of average milk has grown to 2·5 lbs. of starch equivalent, which is no less than 12 per cent. above Kellner's original figure.

The equation given above indicates a ready method of checking these figures. Thousands of cows are now being fed on known rations, so there should be no trouble in finding R. Thousands of cows are now having their milk recorded, so there should be no trouble in finding v to any desired degree of accuracy. Unfortunately very few cowkeepers weigh their cows, so that up to the present we have not been able to get a satisfactory set of figures for either the term Am which cannot be assessed unless the live-weight is known, or for the term gc which of course involves live-weight change. It should be added that the value of c for cows in milk is not known, so that there are two unknowns in the equation:

l = lbs. of starch equivalent per gallon of milk, and
c = lbs. of starch equivalent per lb. of live-weight increase (or decrease).

As soon as figures for the individual rations of 50 to 100 cows, together with their live-weights at regular intervals, their milk yields, and if possible periodical analyses of their milk are available, it will be possible to write an equation for each cow, which can be solved by the least square method for the best values of v and c. If reliable results are to be obtained it is necessary that the cows should vary as widely as possible in live-weight and in milk yield, but that they should all be kept under similar conditions so that their maintenance requirement which includes normal average movement should not vary.

As soon as really accurate values have been found for v and c, the equation can be used to solve other important problems in milk production. It would be possible to calculate for instance the value of l, *i.e.*, the weight of starch equivalent required to make 1 gallon of milk if the starch equivalent were supplied as hay, as roots, as palm kernel cake, and so to settle whether these particular feeding stuffs have or have not a special value, good or bad, for milk production. All that would be required is the live-weights, milk yields, and fat percentages for a considerable number of cows fed on weighed rations of which one or other of these feeding stuffs formed a large proportion. The writers would be glad to collaborate with anyone who has facilities for recording rations, live-weights and yields of milk of large numbers of cows which facilities they do not themselves possess. It is perhaps unnecessary to add that the records would be useless unless made with considerable accuracy.

Finally the writers claim that results worked out as indicated above from records of large numbers of animals kept under normal conditions might be expected to possess a wider practical value than similar results obtained from more refined and accurate experiments on single animals under laboratory conditions. The method is in fact one which makes it possible to extract fundamental principles of general applicability from accurate records of practical experience.

REFERENCES.

(1) Wood, T. B. *Animal Nutrition.* University Tutorial Press, London, 1924. New edn, 1927.

(2) Internat. Kongress für Milchwirtschaft, 1911. Quoted by Armsby, *Nutrition of Farm Animals,* New York, 1917, p. 493.

(3) Ministry of Agriculture, Misc. Publicn, No. 32, Jan. 1927.

(4) Quoted for British feeding stuffs in *Rations for Livestock.*

(5) *Nutrition of Farm Animals.*

(6) Armsby. *Principles of Animal Nutrition,* pp. 263–8.

(7) Reproduced for British Fodders in *Rations for Live Stock.*
(8) *Nutrition of Farm Animals*, Appendix.
(9) The Production Requirement of Fattening Sheep. *J. Min. of Agric.* 1927, p. 295.
(10) *J. Agric. Sci.* 1926, p. 325.
(11) The Production Requirement of Fattening Sheep. *J. Min. of Agric.* 1927, p. 295.
(12) The Starch Equivalent of Swedes, etc. *J. Min. of Agric.* 1927, p. 297.
(13) *Proc. R.S.* B, **95**, 1923.
(14) Du Bois, D. and E. F. *Arch. Intern. Medicine*, **17**, 887 (1916).
(15) *Loc. cit.*
(16) *Report of Committee on rationing of Dairy Cows*, Ministry of Agriculture.

(*Received June 2nd*, 1928.)

THE JOINT INFLUENCE OF THE PERIOD OF LACTATION AND THE AGE OF THE COW ON THE YIELD AND QUALITY OF THE MILK.

By T. J. DRAKELEY and MARGARET K. WHITE.

(Department of Chemistry and Rubber Technology, Northern Polytechnic, London: The British Dairy Farmers' Association, London.)

(With Three Text-figures.)

THE respective effect of the period of lactation and the age of the cow on the yield and quality of the milk have previously been studied separately (see *J. Agric. Sci.* **17**, Pt I, p. 118, "The Influence of the Stage of Lactation and the Breed of the Cow on the Yield and Quality of the Milk," and **17**, Pt III, p. 420, "The Influence of the Age of the Cow on the Yield and Quality of the Milk"), and an analysis of the data has now been made with regard to the joint influence of these factors.

The method of procedure was described in detail in the first of those papers, and may be briefly summarised thus: The analysis of the milks of the cows exhibited at the forty-eight annual Dairy Shows held by the British Dairy Farmers' Association between 1876 and 1925 have been studied with regard to the yield, fat, and solids-not-fat content of the milk of various breeds of cows. The number of these analyses was 6566, and the advantages of their use for the purposes of these papers were mentioned.

The procedure in this case was to calculate the averages from the analyses of the milk of cows of the same age and breed at successive stages of lactation, and to draw curves to pass as nearly as possible through the values so obtained. A series of curves was thus formed, which showed the influence of the stage of lactation on the yield, percentage of fat, and percentage of solids-not-fat of the milk of eight different breeds of cows, for each age from two to nine years.

From these curves the following Tables (I–VIII) were prepared to show independently the influence of both the stage of lactation and the age of the cow on the yield and quality of the milk for the following breeds: Dairy Shorthorn, Jersey, Guernsey, British Friesian, Ayrshire, Lincoln Red Shorthorn, Red Poll, and Kerry Cows. The curves are of a similar form to those already given in the preceding publications, but are in some cases slightly displaced, owing to the elimination of the indeterminate factor.

Table I. *Dairy Shorthorn Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
2.	Yield (lbs.)	30·5	31·2	31·9	31·5	30·2	29·2	28·5	28·0	27·6	27·2	27·0	26·6	26·2	26·0	25·6	25·2	24·9	24·5	24·2	23·9
	Fat (%)	4·00	3·87	3·70	3·57	3·50	3·45	3·42	3·40	3·39	3·42	3·48	3·55	3·62	3·70	3·80	3·90	4·00	4·10	4·20	4·30
	Solids-not-fat (%)	9·40	9·29	9·17	9·11	9·10	9·09	9·09	9·09	9·09	9·09	9·10	9·10	9·12	9·14	9·17	9·20	9·25	9·29	9·35	9·44
3.	Yield (lbs.)	36·9	37·6	38·3	37·9	36·6	35·6	34·9	34·4	34·0	33·6	33·4	33·0	32·6	32·4	32·0	31·6	31·3	30·9	30·6	30·3
	Fat (%)	4·14	4·01	3·84	3·71	3·64	3·59	3·56	3·54	3·53	3·56	3·62	3·69	3·76	3·84	3·94	4·04	4·14	4·24	4·34	4·44
	Solids-not-fat (%)	9·36	9·25	9·13	9·07	9·06	9·05	9·05	9·05	9·05	9·05	9·06	9·06	9·08	9·10	9·13	9·16	9·21	9·25	9·31	9·40
4.	Yield (lbs.)	43·2	43·9	44·6	44·2	42·9	41·9	41·2	40·7	40·3	39·9	39·7	39·3	38·9	38·7	38·3	37·9	37·6	37·2	36·9	36·6
	Fat (%)	4·23	4·10	3·93	3·80	3·73	3·68	3·65	3·63	3·62	3·65	3·71	3·78	3·85	3·93	4·03	4·13	4·23	4·33	4·43	4·53
	Solids-not-fat (%)	9·32	9·21	9·09	9·03	9·02	9·01	9·01	9·01	9·01	9·01	9·02	9·02	9·04	9·06	9·09	9·12	9·17	9·21	9·27	9·36
5.	Yield (lbs.)	48·2	48·9	49·6	49·2	47·9	46·9	46·2	45·7	45·3	44·9	44·7	44·3	43·9	43·7	43·3	42·9	42·6	42·2	41·9	41·6
	Fat (%)	4·24	4·11	3·94	3·81	3·74	3·69	3·66	3·64	3·63	3·66	3·72	3·79	3·86	3·94	4·04	4·14	4·24	4·34	4·44	4·54
	Solids-not-fat (%)	9·29	9·18	9·06	9·00	8·99	8·98	8·98	8·98	8·98	8·98	8·99	8·99	9·01	9·03	9·06	9·09	9·14	9·18	9·24	9·33
6.	Yield (lbs.)	51·2	51·9	52·6	52·2	50·9	49·9	49·2	48·7	48·3	47·9	47·7	47·3	46·9	46·7	46·3	45·9	45·6	45·2	44·9	44·6
	Fat (%)	4·23	4·10	3·93	3·80	3·73	3·68	3·65	3·63	3·62	3·65	3·71	3·78	3·85	3·93	4·03	4·13	4·23	4·33	4·43	4·53
	Solids-not-fat (%)	9·25	9·14	9·02	8·96	8·95	8·94	8·94	8·94	8·94	8·94	8·95	8·95	8·97	8·99	9·02	9·05	9·10	9·14	9·20	9·29
7.	Yield (lbs.)	53·5	54·2	54·9	54·5	53·2	52·2	51·5	51·0	50·6	50·2	50·0	49·6	49·2	49·0	48·6	48·2	47·9	47·5	47·2	46·9
	Fat (%)	4·21	4·08	3·91	3·78	3·71	3·66	3·63	3·61	3·60	3·63	3·69	3·76	3·83	3·91	4·01	4·11	4·21	4·31	4·41	4·51
	Solids-not-fat (%)	9·21	9·10	8·98	8·92	8·91	8·90	8·90	8·90	8·90	8·90	8·91	8·91	8·93	8·95	8·98	9·01	9·06	9·10	9·16	9·25
8.	Yield (lbs.)	54·6	55·3	56·0	55·6	54·3	53·3	52·6	52·1	51·7	51·3	51·1	50·7	50·3	50·1	49·7	49·3	49·0	48·6	48·3	48·0
	Fat (%)	4·16	4·03	3·86	3·73	3·66	3·61	3·58	3·56	3·55	3·58	3·64	3·71	3·78	3·86	3·96	4·06	4·16	4·26	4·36	4·46
	Solids-not-fat (%)	9·18	9·07	8·95	8·89	8·88	8·87	8·87	8·87	8·87	8·87	8·88	8·88	8·90	8·92	8·95	8·98	9·03	9·07	9·13	9·22
9.	Yield (lbs.)	55·0	55·7	56·4	56·0	54·7	53·7	53·0	52·5	52·1	51·7	51·5	51·1	50·7	50·5	50·1	49·7	49·4	49·0	48·7	48·4
	Fat (%)	4·11	3·98	3·81	3·68	3·61	3·56	3·53	3·51	3·50	3·53	3·59	3·66	3·73	3·81	3·91	4·01	4·11	4·21	4·31	4·41
	Solids-not-fat (%)	9·14	9·03	8·91	8·85	8·84	8·83	8·83	8·83	8·83	8·83	8·84	8·84	8·86	8·88	8·91	8·94	8·99	9·03	9·09	9·18

Table II. *Jersey Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
2.	Yield (lbs.)	23·9	25·3	26·8	27·7	27·9	27·7	27·0	26·5	25·9	25·6	25·4	25·2	24·9	24·7	24·5	24·3	24·1	23·9	23·7	23·5
	Fat (%)	5·29	5·07	4·85	4·85	4·86	4·89	4·95	4·99	5·04	5·09	5·14	5·19	5·24	5·29	5·39	5·39	5·44	5·49	5·54	5·59
	Solids-not-fat (%)	9·67	9·52	9·42	9·40	9·40	9·40	9·40	9·41	9·41	9·41	9·41	9·41	9·41	9·42	9·42	9·42	9·42	9·42	9·42	9·42
3.	Yield (lbs.)	27·2	28·6	30·1	31·0	31·2	31·0	30·3	29·8	29·2	28·9	28·7	28·5	28·2	28·0	27·8	27·6	27·4	27·2	27·0	26·8
	Fat (%)	5·36	5·14	4·92	4·92	4·93	4·96	5·02	5·06	5·11	5·16	5·21	5·26	5·31	5·36	5·41	5·46	5·51	5·56	5·61	5·66
	Solids-not-fat (%)	9·62	9·47	9·37	9·35	9·35	9·35	9·35	9·36	9·36	9·36	9·36	9·36	9·36	9·37	9·37	9·37	9·37	9·37	9·37	9·37
4.	Yield (lbs.)	29·6	31·0	32·5	33·4	33·6	33·4	32·7	32·2	31·6	31·3	31·1	30·9	30·6	30·4	30·2	30·0	29·8	29·6	29·4	29·2
	Fat (%)	5·43	5·21	4·99	4·99	5·00	5·03	5·09	5·13	5·18	5·23	5·28	5·33	5·38	5·43	5·48	5·53	5·58	5·63	5·68	5·73
	Solids-not-fat (%)	9·57	9·42	9·32	9·30	9·30	9·30	9·30	9·13	9·31	9·31	9·31	9·31	9·31	9·32	9·32	9·32	9·32	9·32	9·32	9·32
5.	Yield (lbs.)	30·8	32·2	33·7	34·6	34·8	34·6	33·9	33·4	32·8	32·5	32·3	32·1	31·8	31·6	31·4	31·2	31·0	30·8	30·6	30·4
	Fat (%)	5·44	5·22	5·00	5·00	5·01	5·04	5·10	5·14	5·29	5·24	5·29	5·34	5·39	5·44	5·49	5·54	5·59	5·64	5·69	5·74
	Solids-not-fat (%)	9·55	9·40	9·30	9·28	9·28	9·28	9·28	9·29	9·29	9·29	9·29	9·20	9·29	9·30	9·30	9·30	9·30	9·30	9·30	9·30
6.	Yield (lbs.)	31·7	33·1	34·6	35·5	35·7	35·5	34·8	34·3	33·7	33·4	33·2	33·0	32·7	32·5	32·3	32·1	31·9	31·7	31·5	31·3
	Fat (%)	5·43	5·21	4·99	4·99	5·00	5·03	5·09	5·13	5·18	5·23	5·28	5·33	5·38	5·43	5·48	5·53	5·58	5·63	5·68	5·73
	Solids-not-fat (%)	9·48	9·33	9·23	9·21	9·21	9·21	9·21	9·22	9·22	9·22	9·22	9·22	9·22	9·23	9·23	9·23	9·23	9·23	9·23	9·23
7.	Yield (lbs.)	32·5	33·9	35·4	36·3	36·5	36·3	35·6	35·1	34·5	34·2	34·0	33·8	33·5	33·3	33·1	32·9	33·7	32·5	32·3	32·1
	Fat (%)	5·39	5·17	4·95	4·95	4·96	4·99	5·05	5·09	5·14	5·19	5·24	5·29	5·34	5·39	5·44	5·49	5·54	5·59	5·64	5·69
	Solids-not-fat (%)	9·46	9·31	9·21	9·19	9·19	9·19	9·19	9·20	9·20	9·20	9·20	9·20	9·20	9·21	9·21	9·21	9·21	9·21	9·21	9·21
8.	Yield (lbs.)	32·6	34·0	35·5	36·4	36·6	36·4	35·7	35·2	34·6	34·3	34·1	33·9	33·6	33·4	33·2	36·6	32·8	32·6	32·4	32·2
	Fat (%)	5·31	5·09	4·87	4·87	4·88	4·91	4·97	5·01	5·06	5·11	5·16	5·21	5·27	5·31	5·36	5·41	5·46	5·51	5·56	5·61
	Solids-not-fat (%)	9·44	9·29	9·19	9·17	9·17	9·17	9·17	9·18	9·18	9·18	9·18	9·18	9·18	9·11	9·19	9·19	9·19	9·19	9·19	9·19
9.	Yield (lbs.)	32·6	34·0	35·5	36·4	36·6	36·4	35·7	35·2	34·6	34·3	34·1	33·9	33·6	33·4	33·2	33·0	32·8	32·6	32·4	32·2
	Fat (%)	5·18	4·96	4·74	4·74	4·75	4·78	4·84	4·88	4·93	4·98	5·03	5·08	5·13	5·18	5·23	5·28	5·33	5·38	5·43	5·48
	Solids-not-fat (%)	9·42	9·27	9·17	9·15	9·15	9·15	9·15	9·16	9·16	9·16	9·16	9·16	9·16	9·17	9·17	9·17	9·17	9·17	9·17	9·19

Table III. *Guernsey Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
2.	Yield (lbs.)	26·0	27·5	29·3	29·6	29·0	28·1	27·1	26·6	26·0	25·5	25·0	24·4	24·0	23·4	22·9	22·4	21·9	21·3	20·8	20·3
	Fat (%)	4·94	4·81	4·73	4·72	4·73	4·76	4·79	4·81	4·84	4·88	4·90	4·92	4·94	4·98	5·01	5·04	5·07	5·10	5·11	5·14
	Solids-not-fat (%)	9·43	9·37	9·32	9·30	9·29	9·27	9·27	9·27	9·28	9·29	9·30	9·31	9·30	9·32	9·33	9·35	9·37	9·41	9·47	9·53
3.	Yield (lbs.)	28·9	30·4	32·2	32·5	31·9	31·0	30·0	29·5	28·9	28·4	27·9	27·3	26·9	26·3	25·8	25·3	24·8	24·2	23·7	23·2
	Fat (%)	4·97	4·84	4·76	4·75	4·76	4·79	4·82	4·84	4·87	4·91	4·93	4·95	4·97	5·01	5·04	5·07	5·10	5·13	5·14	5·17
	Solids-not-fat (%)	9·42	9·36	9·31	9·29	9·26	9·26	9·26	9·26	9·27	9·28	9·29	9·30	9·31	9·31	9·32	9·34	9·36	9·40	9·46	9·52
4.	Yield (lbs.)	31·0	32·5	34·3	34·6	34·0	33·1	32·1	31·6	31·0	30·5	30·0	29·4	29·0	28·4	27·9	27·4	26·9	26·3	25·8	25·3
	Fat (%)	4·96	4·83	4·75	4·74	4·75	4·78	4·81	4·83	4·86	4·90	4·92	4·94	4·96	5·00	5·03	5·06	5·09	5·12	5·13	5·16
	Solids-not-fat (%)	9·40	9·34	9·29	9·27	9·24	9·24	9·24	9·24	9·25	9·26	9·27	9·28	9·29	9·29	9·30	9·32	9·34	9·38	9·44	9·50
5.	Yield (lbs.)	32·5	34·0	35·8	36·1	35·5	34·6	33·6	33·1	32·5	32·0	31·5	30·9	30·5	29·9	29·4	28·9	28·4	27·8	27·3	26·8
	Fat (%)	4·93	4·80	4·72	4·71	4·72	4·75	4·79	4·80	4·83	4·87	4·89	4·91	4·93	4·97	5·00	5·03	5·06	5·09	5·10	5·13
	Solids-not-fat (%)	9·35	9·29	9·24	9·22	9·19	9·19	9·19	9·19	9·20	9·21	9·22	9·23	9·24	9·24	9·25	9·27	9·29	9·33	9·39	9·45
6.	Yield (lbs.)	33·4	34·9	36·7	37·0	36·4	35·5	34·5	34·0	33·4	32·9	32·4	31·8	31·4	30·8	30·3	29·8	29·3	28·7	28·2	27·7
	Fat (%)	4·90	4·77	4·69	4·68	4·69	4·72	4·75	4·77	4·79	4·84	4·86	4·88	4·89	4·94	4·97	5·00	5·03	5·06	5·07	5·10
	Solids-not-fat (%)	9·30	9·24	9·19	9·17	9·14	9·14	9·14	9·14	9·15	9·16	9·17	9·18	9·19	9·19	9·21	9·22	9·24	9·28	9·34	9·40
7.	Yield (lbs.)	33·9	35·4	37·2	37·5	36·9	36·0	35·0	34·5	33·9	33·4	32·9	32·3	31·9	31·3	30·8	30·3	29·8	29·2	28·7	28·2
	Fat (%)	4·82	4·69	4·61	4·60	4·61	4·64	4·67	4·69	4·71	4·76	4·78	4·80	4·81	4·86	4·89	4·92	4·59	4·98	4·99	5·02
	Solids-not-fat (%)	9·25	9·19	9·14	9·12	9·09	9·09	9·09	9·09	9·10	9·11	9·12	9·13	9·14	9·14	9·15	9·17	9·19	9·23	9·29	9·35
8.	Yield (lbs.)	33·9	35·4	37·2	37·5	36·9	36·0	35·0	34·5	33·9	33·4	32·9	32·3	31·9	31·3	30·8	30·3	29·8	29·2	28·7	28·2
	Fat (%)	4·75	4·62	4·54	4·53	4·54	4·57	4·60	4·62	4·64	4·69	4·71	4·73	4·74	4·79	4·82	4·85	4·88	4·91	4·92	4·95
	Solids-not-fat (%)	9·22	9·16	9·11	9·09	9·06	9·06	9·06	9·06	9·07	9·08	9·09	9·10	9·11	9·11	9·12	9·14	9·16	9·20	9·26	9·32

Table IV. *British Friesian Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
2.	Yield (lbs.)	42·8	44·3	44·8	43·0	40·3	38·0	36·3	34·8	33·8	32·8	32·1	31·6	31·0	30·3	29·6	28·8
	Fat (%)	3·90	3·77	3·60	3·50	3·41	3·37	3·36	3·37	3·40	3·46	3·53	3·61	3·70	3·80	3·88	3·93
	Solids-not-fat (%)	9·15	9·06	8·92	8·85	8·83	8·82	8·82	8·82	8·82	8·82	8·82	8·82	8·82	8·82	8·83	8·83
3.	Yield (lbs.)	49·3	50·8	51·3	49·5	46·8	44·5	42·8	41·3	40·3	39·3	38·6	38·1	37·5	36·8	36·1	35·3
	Fat (%)	4·01	3·88	3·71	3·61	3·52	3·48	3·47	3·48	3·51	3·57	3·64	3·72	3·81	3·91	3·99	4·04
	Solids-not-fat (%)	9·14	9·05	8·91	8·84	8·82	8·81	8·81	8·81	8·81	8·81	8·81	8·81	8·81	8·81	8·82	8·82
4.	Yield (lbs.)	53·8	55·3	55·8	54·0	51·3	49·0	47·3	45·8	44·8	43·8	43·1	42·6	42·0	41·3	40·6	39·8
	Fat (%)	4·07	3·94	3·77	3·67	3·58	3·54	3·53	3·54	3·57	3·63	3·70	3·78	3·87	3·97	4·05	4·10
	Solids-not-fat (%)	9·13	9·04	8·90	8·83	8·81	8·80	8·80	8·80	8·80	8·80	8·80	8·80	8·80	8·80	8·81	8·81
5.	Yield (lbs.)	57·4	58·9	59·4	57·6	54·9	52·6	50·9	49·4	48·4	47·4	46·7	46·2	45·6	44·9	44·2	43·4
	Fat (%)	4·08	3·95	3·78	3·68	3·59	3·55	3·54	3·55	3·58	3·64	3·71	3·79	3·88	3·98	4·06	4·11
	Solids-not-fat (%)	9·12	9·03	8·89	8·82	8·80	8·79	8·79	8·79	8·79	8·79	8·79	8·79	8·79	8·79	8·80	8·80
6.	Yield (lbs.)	60·1	61·6	62·1	60·3	57·6	55·3	53·6	52·1	51·1	50·1	49·4	48·9	48·3	47·6	46·9	46·1
	Fat (%)	4·05	3·92	3·75	3·65	3·56	3·52	3·51	3·52	3·55	3·61	3·68	3·76	3·85	3·95	4·03	4·08
	Solids-not-fat (%)	9·11	9·02	8·88	8·81	8·79	8·78	8·78	8·78	8·78	8·78	8·78	8·78	8·78	8·78	8·79	8·79
7.	Yield (lbs.)	62·0	63·5	64·0	62·2	59·5	57·2	55·5	54·0	53·0	52·0	51·3	50·8	50·2	49·5	48·8	48·0
	Fat (%)	3·97	3·84	3·67	3·57	3·48	3·44	3·43	3·44	3·48	3·53	3·60	3·68	3·77	3·87	3·95	4·00
	Solids-not-fat (%)	9·10	9·01	8·87	8·80	8·78	8·77	8·77	8·77	8·77	8·77	8·77	8·77	8·77	8·77	8·78	8·78

Table V. *Ayrshire Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100
2.	Yield (lbs.)	35·3	36·8	39·6	39·2	38·8	36·9	35·4	33·8	32·3	30·8
	Fat (%)	4·65	4·49	4·23	4·07	3·93	3·88	3·85	3·84	3·83	3·83
	Solids-not-fat (%)	9·53	9·38	9·19	9·12	9·04	9·00	8·98	8·98	8·98	8·98
3.	Yield (lbs.)	40·1	41·6	43·8	44·0	43·6	41·7	40·2	38·6	37·1	35·6
	Fat (%)	4·74	4·58	4·32	4·16	4·02	3·97	3·94	3·93	3·92	3·92
	Solids-not-fat (%)	9·46	9·31	9·12	9·05	8·87	8·93	8·91	8·91	8·91	8·91
4.	Yield (lbs.)	43·6	45·1	47·3	47·5	47·1	45·2	43·7	42·1	40·6	39·1
	Fat (%)	4·71	4·55	4·29	4·13	3·90	3·94	3·91	3·90	3·89	3·89
	Solids-not-fat (%)	9·40	9·26	9·07	9·00	8·92	8·88	8·86	8·86	8·86	8·86
5.	Yield (lbs.)	46·3	47·8	50·0	50·2	49·8	47·9	46·1	44·8	43·3	41·8
	Fat (%)	4·60	4·44	4·18	4·02	3·88	3·83	3·80	3·79	3·78	3·78
	Solids-not-fat (%)	9·34	9·16	9·00	8·93	8·85	8·81	8·79	8·79	8·79	8·79
6.	Yield (lbs.)	48·2	49·7	51·9	52·1	50·7	48·8	47·3	45·7	44·2	42·7
	Fat (%)	4·46	4·30	4·04	3·88	3·74	3·69	3·66	3·65	3·64	3·64
	Solids-not-fat (%)	9·29	9·14	8·95	8·88	8·80	8·76	8·74	8·74	8·74	8·74
7.	Yield (lbs.)	49·5	51·0	53·2	53·4	52·0	50·1	48·6	47·0	45·5	44·0
	Fat (%)	4·25	4·09	3·83	3·67	3·53	3·48	3·45	3·44	3·43	3·43
	Solids-not-fat (%)	9·22	9·07	8·88	8·81	8·73	8·69	8·67	8·67	8·67	8·67
8	Yield (lbs.)	50·1	51·6	53·8	54·0	52·6	50·7	49·2	47·6	46·1	44·6
	Fat (%)	3·98	3·82	3·56	3·40	3·26	3·21	3·18	3·17	3·16	3·16
	Solids-not-fat (%)	9·16	9·01	8·82	8·75	8·67	8·63	8·61	8·61	8·61	8·61

Table VI. *Lincoln Red Shorthorn Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100
2.	Yield (lbs.)	34·5	35·2	35·0	33·2	31·8	30·9	30·2	30·0	29·7	29·4
	Fat (%)	4·03	3·87	3·62	3·50	3·45	3·42	3·42	3·42	3·43	3·46
	Solids-not-fat (%)	9·41	9·33	9·22	9·16	9·10	9·08	9·06	9·06	9·06	9·06
3.	Yield (lbs.)	40·5	41·2	41·0	39·2	37·8	36·9	36·2	36·0	35·7	35·4
	Fat (%)	4·21	4·05	3·80	3·68	3·63	3·60	3·60	3·60	3·61	3·64
	Solids-not-fat (%)	9·35	9·27	9·16	9·10	9·04	9·02	9·00	9·00	9·00	9·00
4.	Yield (lbs.)	45·5	46·2	46·0	44·2	42·8	41·9	41·2	41·0	40·7	40·4
	Fat (%)	4·23	4·07	3·82	3·70	3·65	3·62	3·62	3·62	3·63	3·66
	Solids-not-fat (%)	9·30	9·22	9·11	9·05	8·99	8·97	8·95	8·95	8·95	8·95
5.	Yield (lbs.)	49·3	50·0	49·8	48·0	46·6	45·7	45·0	44·8	44·5	44·2
	Fat (%)	4·21	4·04	3·79	3·67	3·62	3·59	3·59	3·59	3·60	3·63
	Solids-not-fat (%)	9·23	9·15	9·04	8·98	8·92	8·90	8·88	8·88	8·88	8·88
6.	Yield (lbs.)	52·1	52·9	52·7	50·9	49·5	48·6	47·9	47·7	47·4	47·1
	Fat (%)	4·16	4·00	3·75	3·63	3·58	3·55	3·55	3·55	3·56	3·59
	Solids-not-fat (%)	9·17	9·09	8·98	8·92	8·86	8·84	8·82	8·82	8·82	8·82
7.	Yield (lbs.)	54·1	54·9	54·7	52·9	51·5	50·6	49·9	49·7	49·4	49·1
	Fat (%)	4·01	3·94	3·69	3·57	3·52	3·49	3·49	3·49	3·50	3·53
	Solids-not-fat (%)	9·12	9·04	8·93	8·87	8·81	8·79	8·77	8·77	8·77	8·77
8.	Yield (lbs.)	55·1	55·9	55·7	53·9	52·5	51·6	50·9	50·7	50·4	50·1
	Fat (%)	4·03	3·87	3·62	3·50	3·45	3·42	3·42	3·42	3·43	3·46
	Solids-not-fat (%)	9·06	8·98	8·87	8·81	8·75	8·73	8·71	8·71	8·71	8·71

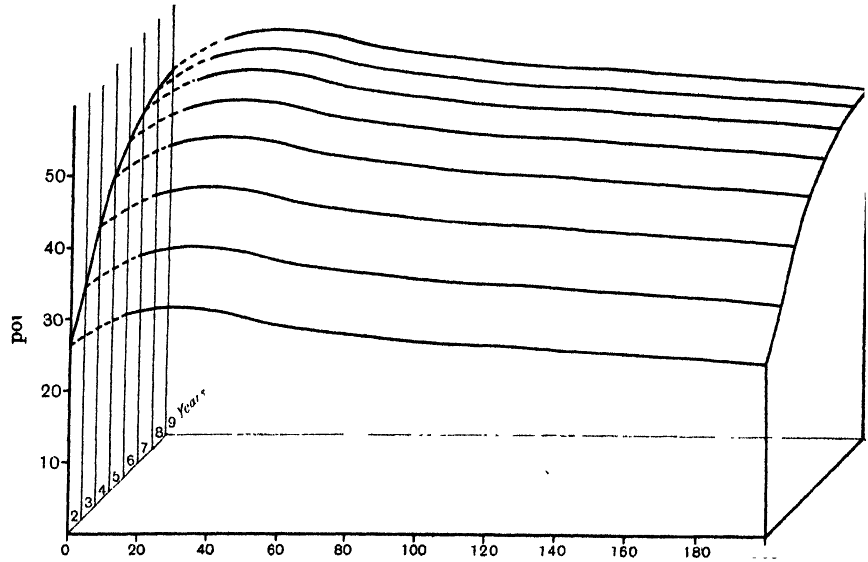
Table VII. *Red Poll Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
2.	Yield (lbs.)	31·7	32·2	32·8	32·5	31·8	30·8	30·0	29·3	28·8	28·4	28·1	27·1	27·1	27·1	26·8	26·5	26·3	26·1	29·5	25·7
	Fat (%)	4·06	3·93	3·77	3·70	3·67	3·65	3·63	3·63	3·63	3·64	3·66	3·67	3·70	3·72	3·76	3·80	3·86	3·92	3·99	4·05
	Solids-not-fat (%)	9·48	9·36	9·22	9·17	9·12	9·12	9·12	9·13	9·16	9·18	9·20	9·21	9·21	9·22	9·23	9·25	9·26	9·27	9·29	9·30
3.	Yield (lbs.)	37·3	37·8	38·4	38·1	37·3	36·4	35·6	34·9	34·4	34·0	33·7	33·3	33·0	32·7	32·4	32·1	31·9	31·7	31·5	31·3
	Fat (%)	4·18	4·05	3·89	3·82	3·79	3·77	3·75	3·75	3·75	3·76	3·78	3·79	3·82	3·84	3·88	3·92	3·98	4·04	4·11	4·17
	Solids-not-fat (%)	9·46	9·34	9·20	9·15	9·10	9·10	9·10	9·11	9·14	9·16	9·18	9·19	9·19	9·20	9·21	9·23	9·24	9·25	9·27	9·28
4.	Yield (lbs.)	42·0	42·5	43·1	42·8	42·0	41·1	40·3	39·6	39·1	38·7	38·4	38·0	37·7	37·4	37·1	36·8	36·6	36·4	36·2	36·0
	Fat (%)	4·18	4·05	3·89	3·82	3·79	3·77	3·75	3·75	3·75	3·76	3·78	3·79	3·22	3·84	3·88	3·92	3·98	4·04	4·11	4·17
	Solids-not-fat (%)	9·41	9·29	9·15	9·10	9·05	9·05	9·05	9·06	9·09	9·11	9·13	9·14	9·14	9·15	9·16	9·18	9·19	9·20	9·22	9·23
5.	Yield (lbs.)	45·1	45·6	46·2	45·9	45·1	44·2	43·4	42·7	42·1	41·8	41·5	41·1	40·8	40·5	40·2	39·9	39·7	39·5	39·3	39·0
	Fat (%)	4·05	3·92	3·76	3·69	3·66	3·64	3·62	3·62	3·62	3·63	3·65	3·66	3·69	3·71	3·75	3·79	3·85	3·91	3·98	4·04
	Solids-not-fat (%)	9·36	9·24	9·10	9·05	9·00	9·00	9·00	9·01	9·04	9·06	9·08	9·09	9·09	9·10	9·11	9·13	9·14	9·15	9·17	9·18
6.	Yield (lbs.)	46·9	47·4	48·0	47·7	46·9	46·0	45·2	44·5	44·0	43·6	43·3	42·9	42·6	42·3	42·0	41·7	41·5	41·3	41·1	40·9
	Fat (%)	3·96	3·83	3·67	3·60	3·57	3·55	3·53	3·53	3·53	3·54	3·56	3·57	3·60	3·62	3·66	3·70	3·76	3·82	3·89	3·95
	Solids-not-fat (%)	9·34	9·22	9·08	9·03	8·98	8·98	8·98	8·99	9·02	9·04	9·06	9·07	9·07	9·08	9·09	9·19	9·12	9·13	9·05	9·16
7.	Yield (lbs.)	48·0	48·5	49·1	48·8	48·0	47·1	46·3	45·6	45·1	44·7	44·4	44·0	43·7	43·4	43·1	42·8	42·6	42·4	42·2	42·0
	Fat (%)	3·91	3·78	3·62	3·55	3·52	3·50	3·48	3·48	3·48	3·49	3·51	3·52	3·55	3·57	3·61	3·65	3·71	3·77	3·84	3·90
	Solids-not-fat (%)	9·31	9·19	9·05	9·00	8·95	8·95	8·95	8·96	8·99	9·01	9·03	9·04	9·04	9·05	9·06	9·08	9·09	9·10	9·12	9·13
8.	Yield (lbs.)	48·4	48·9	49·5	49·2	48·4	47·5	46·7	46·0	45·5	45·1	44·8	44·5	44·1	43·8	43·5	43·2	43·0	42·8	42·6	42·4
	Fat (%)	3·89	3·76	3·60	3·53	3·50	3·48	3·46	3·46	3·46	3·47	3·49	3·50	3·53	3·55	3·59	3·63	3·69	3·75	3·82	3·88
	Solids-not-fat (%)	9·29	9·17	9·03	8·98	8·93	8·93	8·93	8·94	8·97	8·99	9·01	9·02	9·02	9·03	9·04	9·06	9·07	9·08	9·10	9·11
9.	Yield (lbs.)	48·5	49·0	49·6	49·3	48·5	47·6	46·8	46·1	45·6	45·2	44·9	44·6	44·2	43·9	43·6	43·3	43·1	42·9	42·7	42·5
	Fat (%)	3·87	3·74	3·58	3·51	3·48	3·46	3·44	3·44	3·44	3·45	3·47	3·48	3·51	3·53	3·57	3·61	3·67	3·73	3·80	3·86
	Solids-not-fat (%)	9·26	9·14	9·00	8·95	8·90	8·90	8·90	8·91	8·94	8·96	8·98	8·99	8·99	9·09	9·01	9·03	9·04	9·05	9·07	9·06

Table VIII. *Kerry Cows.*

Age (years)	Days lactation ...	15	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
2.	Yield (lbs.)	20·8	22·0	22·6	22·0	20·5	18·5	17·2	16·2	15·2	14·5	13·7	13·5	13·0	12·6	12·3	11·9	11·6	11·4	11·0	10·7
	Fat (%)	4·76	4·61	4·42	4·32	4·26	4·26	4·26	4·27	4·30	4·34	4·41	4·47	4·51	4·56	4·63	4·70	4·80	4·87	4·97	5·07
	Solids-not-fat (%)	9·54	9·46	9·37	9·32	9·29	9·26	9·25	9·25	9·25	9·25	9·25	9·25	9·25	9·25	9·25	9·26	9·26	9·27	9·27	9·28
3.	Yield (lbs.)	27·0	28·2	28·8	28·2	26·7	24·7	23·5	22·4	21·4	20·7	19·9	19·7	19·2	18·8	18·5	18·1	17·8	17·6	17·2	16·9
	Fat (%)	4·79	4·64	4·45	4·35	4·29	4·29	4·29	4·30	4·33	4·37	4·44	4·50	4·54	4·59	4·66	4·73	4·83	4·90	5·00	5·10
	Solids-not-fat (%)	9·54	9·46	9·37	9·32	9·29	9·26	9·25	9·25	9·25	9·25	9·25	9·25	9·25	9·25	9·25	9·26	9·26	9·27	9·27	9·28
4.	Yield (lbs.)	21·8	33·0	33·6	33·0	31·5	29·5	28·3	27·2	26·2	25·5	24·7	24·5	24·0	23·6	23·3	22·9	22·6	22·4	22·0	21·7
	Fat (%)	4·77	4·62	4·43	4·33	4·27	4·27	4·27	4·28	4·31	4·35	4·42	4·48	4·52	4·57	4·64	4·71	4·81	4·88	4·98	5·08
	Solids-not-fat (%)	9·46	9·38	9·29	9·24	9·21	9·18	9·17	9·17	9·17	9·17	9·17	9·17	9·17	9·17	9·17	9·18	9·18	9·19	9·19	9·20
5.	Yield (lbs.)	35·4	36·6	37·2	36·6	35·1	33·1	31·9	30·8	29·8	29·1	28·3	28·1	27·6	27·2	26·9	26·5	26·2	26·0	25·6	25·3
	Fat (%)	4·66	4·51	4·32	4·22	4·16	4·16	4·16	4·17	4·20	4·24	4·31	4·37	4·41	4·46	4·53	4·60	4·70	4·77	4·87	4·97
	Solids-not-fat (%)	9·36	9·28	9·19	9·14	9·11	9·08	9·07	9·07	9·07	9·07	9·07	9·07	9·07	9·07	9·07	9·08	9·08	9·09	9·09	9·10
6.	Yield (lbs.)	38·0	39·2	39·8	39·2	37·7	35·7	34·5	33·4	32·4	31·7	30·9	30·7	30·2	29·8	29·5	29·1	28·8	28·6	28·2	27·9
	Fat (%)	4·51	4·36	4·17	4·07	4·01	4·01	4·01	4·02	4·05	4·09	4·16	4·22	4·26	4·31	4·38	4·45	4·55	4·62	4·72	4·82
	Solids-not-fat (%)	9·29	9·21	9·12	9·07	9·04	9·01	9·00	9·00	9·00	9·00	9·00	9·00	9·00	9·00	9·00	9·01	9·01	9·02	9·02	9·03
7.	Yield (lbs.)	40·0	41·2	41·8	41·2	39·7	37·7	36·5	35·4	34·4	33·7	32·9	32·7	32·2	31·8	31·5	31·1	30·8	30·6	30·2	29·9
	Fat (%)	4·35	4·20	4·01	3·91	3·85	3·85	3·85	3·86	3·89	3·93	4·00	4·06	4·10	4·15	4·22	4·29	4·39	4·46	4·56	4·66
	Solids-not-fat (%)	9·24	9·16	9·07	9·02	8·99	8·96	8·95	8·95	8·95	8·95	8·95	8·95	8·95	8·95	8·95	8·96	8·96	8·97	8·97	8·98
8.	Yield (lbs.)	41·3	42·5	43·1	42·5	41·0	39·0	37·8	36·7	35·7	35·0	34·2	34·0	33·5	33·1	32·8	32·4	32·1	31·9	31·5	31·2
	Fat (%)	4·24	4·09	4·00	3·80	3·74	3·74	3·74	3·75	3·78	3·82	3·89	3·95	3·99	4·04	4·11	4·18	4·28	4·35	4·45	4·55
	Solids-not-fat (%)	9·21	9·13	9·04	8·99	8·96	8·93	8·92	8·92	8·92	8·92	8·92	8·92	8·92	8·92	8·92	8·93	8·93	8·94	8·94	8·95
9.	Yield (lbs.)	42·0	43·2	43·8	43·2	41·7	39·7	38·5	37·4	36·4	35·7	34·9	34·7	34·2	33·8	33·6	33·1	32·8	32·6	32·2	31·9
	Fat (%)	4·17	4·02	3·93	3·73	3·67	3·67	3·67	3·68	3·71	3·75	3·82	3·88	3·92	3·97	4·04	4·11	4·21	4·28	4·34	4·48
	Solids-not-fat (%)	9·15	9·07	8·98	8·93	8·90	8·87	8·86	8·86	8·86	8·86	8·86	8·86	8·86	8·86	8·86	8·87	8·87	8·88	8·88	8·89

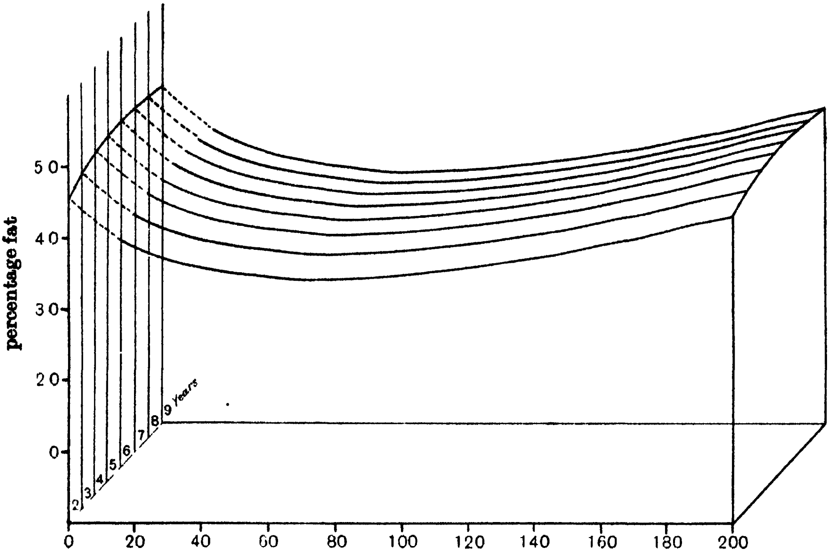
The Influence of the Stage of Lactation appears to be the same for cows of all ages, up to 200 days from calving, which is the maximum time obtainable from the existing data. Thus, it was found that for each breed the curves for the yield, percentage fat, and percentage solids-not-fat at successive ages were respectively parallel. The general shape of the curves was similar to that given in the first paper, and the minimum percentage of fat and maximum yield of milk occurred at approximately the times shown in the former publications (*loc. cit.*).



Yield, age, days since calving

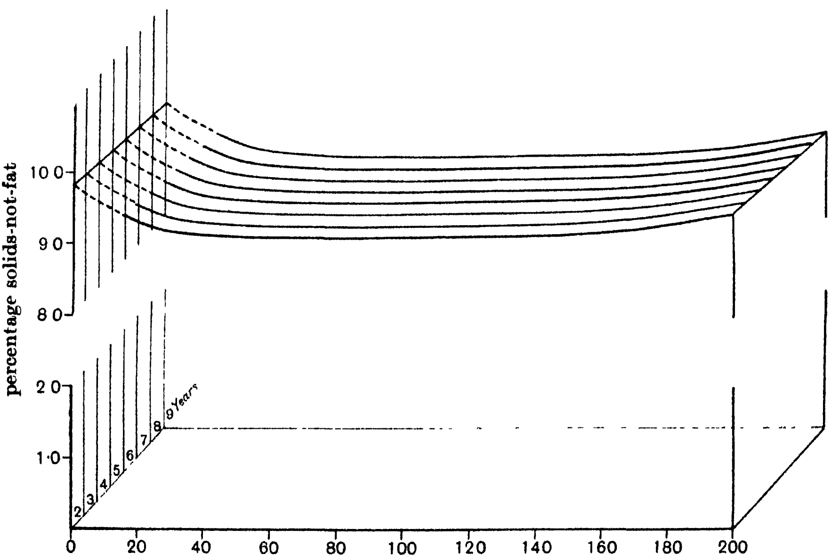
Fig. 1.

The Influence of Age. It follows from the statement made in the previous paragraph that the influence of the age of the cow on the milk is the same at all stages of the lactation period, and the curves showing the effect of age on the cows of the same breed at varying lactation periods were parallel. The shape of these curves was again similar to those described in the second paper (*loc. cit.*), but the variation is slightly greater than that shown between the lactation curves, due to the fact that in several breeds the number of days since calving became greater with the increased age of the cows under consideration. For example, in the second paper (*loc. cit.*), the yield of the Red Poll Cows increased from 30·9 lbs. at two years of age and fifty-four days' lactation to 44·0 lbs. at nine years and eighty-six days' lactation, whereas from Table VII in



Percentage fat, age, days since calving

Fig. 2.



Percentage solids-not-fat, age, days since calving

Fig. 3.

this paper it will be seen that at sixty days the yield increases from 30·8 lbs. at two years old to 47·6 lbs. at nine years old. This shows that the influence of age on the yield of the Red Poll Cows, as described in Paper II, was slightly modified by the increase in lactation.

A similar slight displacement is observed in other breeds, for example, the Dairy Shorthorn and Jersey Cows.

The figures (Figs. 1–3) show the joint effect of the age of the cow, and the period of lactation on the yield, percentage of fat, and percentage of solids-not-fat of Dairy Shorthorn Cows. Similar figures may be obtained for the other breeds by plotting the solid figures represented by the values in Tables II–VIII.

The equation for the surface of the solid figure so obtained for the yield of Dairy Shorthorn Cows has been worked out, and is as follows:

$$w = [3x(x-14)\,e^{-\frac{x}{10}} - 2x - 21{\cdot}78\,(9-y)^{2{\cdot}16} + 3310]/60,$$

where

w = yield of milk in pounds,

x = lactation period in days,

y = age in years.

It is, however, too complicated to be of any practical value; and a similar disadvantage applies to the respective equations for the solid figures for the percentages of fat and of solids-not-fat.

(*Received March* 31*st*, 1928.)

WART DISEASE INFECTION TESTS.

By H. BRYAN, B.Sc.

(*Potato Testing Station, National Institute of Agricultural Botany, Ormskirk.*)

(With Plates X and XI.)

Previous Work.

In recent years several methods of determining the reaction of potatoes to wart disease (*Synchytrium endobioticum*) under indoor conditions have been published by different authors. The most recent method, and the results obtained by its use were published in the July 1926 and July 1927 numbers of the *Scottish Journal of Agriculture*. The method consists of placing sprouted potatoes rose-end downwards in moist sphagnum moss. In some cases the moss was previously impregnated with powdered rotted wart, in others the moss was left untreated. The tubers were watered with washings of actively growing wart, sufficient water being applied each day to keep the bed of sphagnum very wet. The dishes were placed uncovered on laboratory benches; the day temperature of the laboratory ranging from 10° to 20° C.

The method did not prove infallible. Of 687 control tubers of known susceptible varieties which were tested, 176 failed to develop wart. The length of time the experiment lasted is not given. In 1927 much work was done on this method at the Potato Testing Station of the National Institute of Agricultural Botany at Ormskirk which confirmed the fallibility of the method, the amount of infection obtained on known susceptible varieties varying from 17 per cent. to 20 per cent. after three months' treatment. Apart from the lack of infection obtained and the length of time involved in the experiment, a serious objection to the method was the high percentage of rotting of the tubers under test.

A New Method.

A more rapid and reliable method was sought and work has been carried out during the winter 1927–8 on a method indicated by Miss Glynne (1). This method consists of infecting by summer sporangia the clean growing sprouts of the tubers under test.

The technique used by Miss Glynne is as follows. Fresh growing wart tissue is pinned on to tubers in close contact with the young sprout.

It is necessary that a film of water should connect the warted tissue with the young sprouts. To ensure this the method adopted was to place the tubers with the attached warts on a piece of filter paper dipping into a vessel of water and supported over it by means of a wire frame. The tubers were sprayed with water from a fine sprayer once or twice a day and then covered with a sheet of damp filter paper and the whole covered with a bell jar. In this way about a dozen tubers were tested at the same time.

The method was tried out at Ormskirk on a large scale during the winter 1927–8 and appears to be infallible. The apparatus, as used by Miss Glynne, was very much simplified and consisted of wooden structures built on a bench in a greenhouse in the form of boxes, the tops of which were fitted with glass lids. Two structures were made, one 12 in. and the other 6 in. deep and were capable of holding 300 and 100 tubers respectively. The larger box was 4 ft. long and 3 ft. wide, and the smaller 2 ft. long by 1 ft. wide. Wire frames were placed in the bottom of the boxes for the purpose of drainage and covered with damp thin flannel. The tubers with small pieces of fresh developing wart pinned on to the eyes were placed rose-end upwards in wire baskets 10 in. square and 3 in. deep, each capable of holding between 25 and 30 tubers, the tubers loosely supporting each other (Figs. 1 and 2). After spraying with tap or rain water from a fine hand sprayer, the tubers were covered with a further layer of damp flannel. Half a pint of water was used for spraying 300 tubers reasonably closely spaced and was applied once daily, the covering layer of flannel being removed at each spraying and replaced after being soaked in water, any excess of water being wrung out. By this means it is found that the film of moisture connecting the young shoots and the attached pieces of wart was retained far more efficiently than with the use of filter paper, and it is emphasised that the essential factor of this method is the maintenance, as far as possible, of the film of moisture between the young shoots and the attached pieces of wart. The temperature of the greenhouse averaged 15° C. in the daytime but was occasionally as low as 5° C. in the early morning.

The number of eyes treated was three or four per tuber, the sprouts of which were just breaking. The infecting warts were renewed immediately the pieces rotted, usually in 5 or 6 days, different eyes being treated as far as possible at each renewal. Small tags of linen tape numbered with Indian ink and pinned on the tubers formed a simple means of identification.

The success of the method depends on the use of sound slightly

sprouted tubers—the sprouts preferably should not be more than one-tenth to one-eighth of an inch long—the careful pinning on of the fresh wart and its removal when rotten, the avoidance of too high a temperature, and excess of water. The flannel covering the tubers under test must be kept moist only and not saturated.

The whole of the work was carried out in a heated greenhouse up to the end of March. During April heat was only occasionally required at night and after this month was entirely discontinued. The method can be carried out in any room or sprouting shed during the winter months provided a reasonable supply of heat is available.

RESULTS OBTAINED WITH THE NEW METHOD AT ORMSKIRK.

A large number of known susceptible tubers was tested by this method during the early part of 1928. Infection took place in every instance except where isolated cases of rotting occurred, and all tubers bore typical wart excrescences within 28 days from the beginning of the treatment, and 90 per cent. within 21 days (Fig. 3). Infection was in some cases detected within 10 days. Owing to the small amount of water, as compared with the sphagnum moss method, the moderate temperature employed and the short duration of the experiment, the amount of rotting was slight and when it occurred was mainly confined to the sprouts. As soon as infection appeared the infected tubers were removed and buried in moist sand in the greenhouse in order to hasten wart development; with this treatment growth of the wart was in most cases remarkably rapid. To avoid rotting it is essential that the sand be kept moist only, and not water-logged. Large growths similar to those found on susceptible varieties growing in infected land in July and August were obtained in the winter months within four or five weeks of the setting up of the test (Fig. 4).

Some results of this preliminary work are given below:

Table I.

Variety	No. of tubers tested	Date set up	No. of tubers infected after 21 days	28 days	Remarks
Arran Chief	47	15. 12. 27	27	45	Two tubers rotted
Arran Chief	50	23. 2. 28	34	47	Two tubers rotted; one tuber was "blind"
Sharpe's Express	14	13. 3. 28	14	14	—

In order to gain further experience of the practicability of the method, 82 seedlings were obtained from two seed-potato firms for test. The

susceptibility of 33 stocks was established within 28 days from the commencement of the test. Twenty-seven seedlings were received from one firm, three tubers of each were tested and 13 stocks proved susceptible. All three tubers of each susceptible seedling were infected. The 82 seedlings represented a total of 135 tubers, the whole of which were fit for planting at the conclusion of the test, no rotting of any kind having occurred.

Check Test of Method and Analysis of Results.

To test the reliability of the method Dr R. N. Salaman, Director of The Potato Virus Research Station, Cambridge, forwarded under numbers 110 small samples of either two or three tubers of different varieties, the immunity or susceptibility of which had already been officially established by the field test, and the identity of which was known to the sender but unknown at Ormskirk.

The reaction to wart was correctly ascertained in the case of 103 samples within 24 days. On the identity of the samples being disclosed it was found that 31 established immune and 18 susceptible varieties were represented, most of the varieties being repeated several times. An analysis of the results and the names of the varieties are given in Tables II and III. One sample was unfit for test, leaving six ambiguous cases to be discussed.

From the following tables it is seen that out of a total of 207 tubers tested 10 rotted within 24 days. It is noteworthy that an equal percentage of rotting took place within six weeks amongst the untreated surplus tubers left in the sprouting boxes. It was found that tubers affected with blight (*Phytophthora infestans*), dry-rot (*Fusarium caeruleum*) or pink-rot (*Phytophthora erythroseptica*) rotted rapidly and were useless for test.

Ambiguous Cases.

In two samples (Duke of York and Edzell Blue) the reaction to wart could not be ascertained owing to rotting. In a third sample although excrescences were noticed on both tubers within 24 days, these were not definitely identified as wart disease until the 37th day. This sample—a white-flowering Sharpe's Express—is of interest in that it is the only case amongst susceptible varieties tested where the warts formed were not typical within four weeks. Infection presumably did not take place until the second renewal of the pieces of wart. The tubers were not sprouted when the test commenced. In two further cases misnaming

Table II.

Immune varieties	No. of samples	No. of tubers tested	No. of tubers sound and free from wart after 24 days	Remarks
Arran Rose	1	2	1	1 rotted
Ben Cruachan	1	2	2	
Immune Ashleaf	4	8	8	
Edzell Blue	2	4	4	
International Kidney	1	2	2	
Di-vernon	4	8	7	1 rotted
Duke of Perth	2	4	4	
Catriona	3	6	6	
Early Market	1	2	2	
Lord Tennyson	1	2	2	
Arran Consul	3	6	6	
Arran Victory	1	2	2	
Snowdrop	3	6	5	1 rotted
America	2	4	4	
Abundance	1	2	2	
Golden Wonder	3	6	6	
Glencoe	1	2	2	
Alpha	1	2	2	
Lochar	2	4	4	
Tinwald Perfection	2	4	4	
Gigantic	1	2	2	
Templar	2	4	4	
Crusader	2	4	4	
Great Scot	2	4	4	
King George	2	4	4	
Majestic	1	2	2	
Kerr's Pink	2	4	4	
Arran Comrade	2	5	4	1 rotted
Rhoderic Dhu	1	2	2	
Flourball	1	2	2	
Champion	2	4	4	
Totals	57	115	111	4

Table III.

Susceptible varieties	No. of samples	No. of tubers tested	No. of tubers warted and sound after 24 days	Remarks
Arran Chief	3	6	6	
Beauty of Hebron	2	4	4	
Sharpe's Express	4	8	6	2 rotted
British Queen	3	6	5	1 rotted
Evergood	3	6	6	
Field Marshall	4	8	8	
Sir J. Llewelyn	3	6	6	
Early Rose	2	4	4	
Rycroft Purple	2	4	3	1 rotted
Satisfaction	1	2	2	
Sharpe's Victor	2	4	4	
King Edward	3	6	6	
Duke of York	4	8	8	
Epicure	2	4	4	
Myatt's Ashleaf	2	4	4	
Edgecote Purple	2	4	4	
President	2	4	4	
Up-to-Date	2	4	2	2 rotted
Totals	46	92	86	6

of the samples appears to have occurred. Both tubers of a sample supposed to be the immune variety Ally became severely infected. The tubers, however, were of a long kidney shape; the tuber shape of Ally is a flat round or oval. In a supposed sample of Majestic one tuber was warted and the remaining tuber rotted. Although all possible care was taken in the sending of the samples, the stocks in question had not been kept for this specific purpose and were obtained from different sources at very short notice. It is possible, therefore, that admixture or misnaming occurred. Such instances, however, could only have been very exceptional.

The sixth doubtful case referred to was a sample of Ben Cruachan, one tuber of which showed what appeared to be the initial stages of infection. The abnormal sprout, however, rotted before a microscopical examination could be made.

In a further paper by Miss Glynne (2) it is stated that in the case of certain varieties officially certified as immune small protuberances and surface irregularities resembling the earliest symptoms of infection with wart disease sometimes appeared on the shoots during test by this method. Microscopic examination of these showed that infection by the fungus had taken place. Further development of the parasite, that is, re-infection by summer sporangia, and subsequent formation of winter sporangia were not detected, and the minute protuberances did not develop further.

Ben Cruachan is mentioned as one of the immune varieties showing this abnormality. A further sample, therefore, of seven tubers was tested and two of these showed what appeared to be the earliest symptoms of infection. That infection had occurred in one case as indicated by Miss Glynne was confirmed by Dr G. H. Pethybridge, of the Ministry of Agriculture's Plant Pathological Laboratory, Harpenden, who kindly undertook the examination of the tubers. The remaining five tubers of the sample remained free from any signs of infection during prolonged treatment. These irregularities have not yet been detected on any other immune varieties at Ormskirk although the treatment was in many cases continued for six weeks. It would be of interest to investigate whether similar phenomena occur in the field. In view of the fact that warts develop on all underground parts of the susceptible plant except the roots, the chances of similar infection must be great, and probably occur, but have not been detected. If they do they have so far evaded the writer's observation, nor has reference to such been found in the literature.

The occurrence of occasional abnormal proliferations of the tissue on immune varieties induced by the artificial conditions and not caused by

the wart disease organism presented no practical difficulties. The development of the wart excrescences on susceptible varieties when infection had taken place was rapid and the determination of the susceptibility of the stocks was made precisely as it is made in the field test.

SUPPLY OF INFECTIVE MATERIAL.

At the beginning of the work lack of growing wart was a severe handicap, enough only being available in December to treat the original set of Arran Chief; as soon, however, as wart was formed on these tubers it was used for further tests. It was not until the end of April, during which month but a few tubers were under test and during which time the warts on the now large number of infected tubers buried in sand were allowed time to develop, that a copious supply of green wart was available for the treatment of samples taken from each stock entered for the official immunity trials, the test of which was begun in the first week in May.

The supply of wart can easily be maintained in future years by treating a number of early susceptible tubers during September with fresh growing wart obtained from the field. A supply once having been established, fresh wart could also be assured throughout the year by infecting susceptible tubers at different periods.

When warts are cut from tubers for infection purposes, a small portion of the basal wart should be left on the tuber. The cutting may be very drastic, for if the tuber be again buried in sand re-infection takes place and it will serve as a source of further infective material. Some tubers yielded a periodic supply of wart for three months in this way at Ormskirk.

ADVANTAGES OF THE METHOD.

Field testing for immunity from Wart Disease requires a large number of tubers, and may, under unfavourable conditions, take as many as three years. Indoor testing, on the other hand, can be satisfactorily carried out on as few as three tubers, the results are forthcoming in three or four weeks from the beginning of the test, and the trial can be carried out at any time of the year. Moreover, a large number of varieties can be tested in a small space, optimum conditions can be maintained independently of external weather conditions, and the breeder is enabled to discard his susceptible seedlings at the earliest possible stage.

SUMMARY.

A practical adaptation of a method devised by Miss Glynne for testing indoors the immunity or susceptibility of potato varieties to wart disease is described. The method consists of infecting by summer sporangia the young sprouts of the tubers under test. Extensive test has given such satisfactory results that there is little doubt that the method is infallible.

The writer wishes to render his grateful thanks to Mrs N. McDermott, who has been actively associated with him throughout the work described and who is largely responsible for the technique employed; to Miss M. D. Glynne, of the Rothamsted Experimental Station, for her many helpful suggestions; to Mr W. H. Parker, Director of the National Institute of Agricultural Botany, Cambridge, for his assistance and advice; to Dr R. N. Salaman for supplying material for test, and to Dr G. H. Pethybridge for his kindness in examining tubers sent to him.

REFERENCES.

(1) GLYNNE, MARY D. (1925). Infection Experiments with Wart Disease of Potatoes, *Synchytrium endobioticum* (Schilb.) Perc. *Ann. App. Biol.* **12**, 34-60.

(2) ——— (1926). Wart Disease of Potatoes: The Development of *Synchytrium endobioticum* (Schilb.) Perc. in "Immune" Varieties. *Ann. App. Biol.* **13**, 358 9.

(*Received June* 5*th*, 1928.)

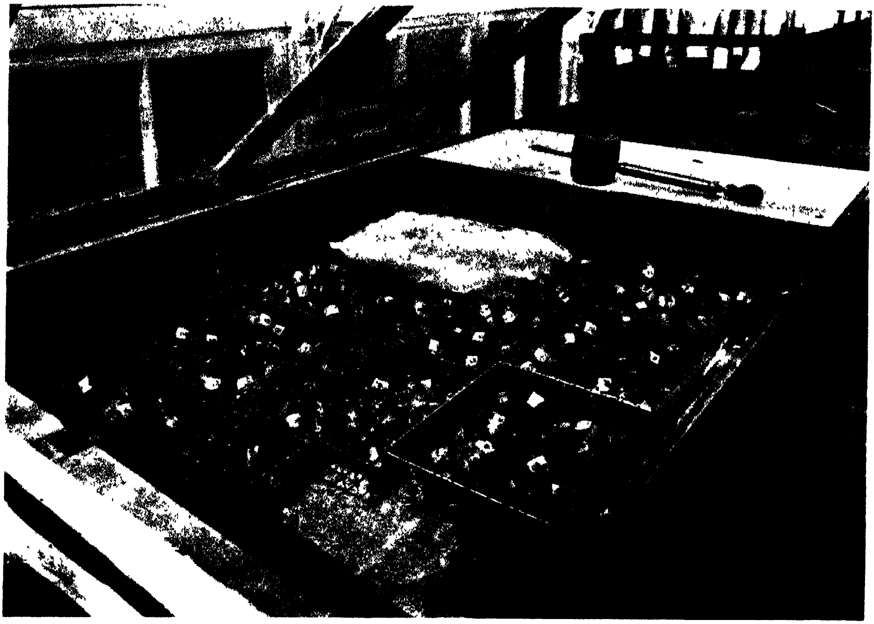


Fig. 1. View of glass-topped box with tubers *in situ*.

Fig. 2. A tray containing tubers under test showing pieces of wart pinned on to the eyes.

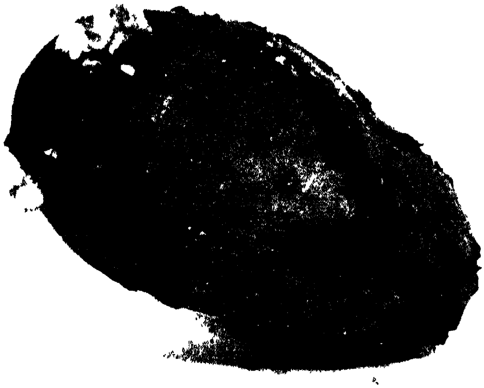


Fig 3. A susceptible tuber after 15 days' treatment.

Fig. 4. Tubers of susceptible varieties showing typical warts 30 days after the commencement of the test.

A SOIL BORING APPARATUS.

By H. GREENE.
(*Wellcome Tropical Research Laboratories, Wad Medani, Sudan*)

(With Two Text-figures.)

It is generally recognised that the study of arid soils frequently necessitates sampling to a depth of 6 feet or more. The most satisfactory way of doing this is to dig a pit and take samples from a vertical face This

Fig. 1. Beginning boring.

method is obviously unsuitable for the examination of small plots and some kind of boring tool must be used instead. In the tenacious clay soil of this area hand augers have been tried without success, but the

mechanical difficulties involved have been largely overcome by use of the apparatus illustrated, which (*a*) secures a truly vertical bore, (*b*) resolves the thrust into two components.

The tripod can be folded up and carried by three men but is rigid when in use. An iron rod of square cross section is suspended from it by means of two pulleys and a wire cable. Into the lower end of this

Fig. 2. Changing position of weights after boring to 3 feet.

rod a shell auger is screwed; the upper end carries a ball race and swivel. Slotted weights which are carried by collars on the iron rod supply the downward thrust; the turning moment is applied by tillers which are also readily detachable. To secure a vertical bore the iron rod is at first steadied by hand, but as soon as the auger has entered the soil slight tension on the cable suffices for the purpose. When the auger has descended a desired depth the boring assembly is wound up and the sample removed. Two windows in the shell auger facilitate this, but

when the soil is sticky the whole auger is detached and another screwed in so as not to delay the boring. It is possible by this means to take a large number of samples from a small area without damaging the crop or disturbing the soil. In speed, accuracy, and working cost this method compares favourably with the use of a hand borer.

Two tools of this type are in use here; they were made by The Millars' Machinery Company, Ltd., of Bishop's Stortford, Hertfordshire. Their long experience in the designing of boring machinery contributes much to the efficiency of this apparatus.

I am indebted to Mr F. G. S. Whitfield for the photographs reproduced.

(*Received March 3rd,* 1928.)

SOIL PROFILE IN THE EASTERN GEZIRA.

By H. GREENE.

(*Wellcome Tropical Research Laboratories, Wad Medani, Sudan.*)

(With One Text-figure.)

In 1925 five hundred square miles of the Eastern Gezira were brought under irrigation. The soil is a heavy clay, salty, alkaline (1) and of low permeability (2). Each year a third of the area is under cotton and is then watered at the rate of 6000 tons per acre per annum whereas the normal annual rainfall is about a quarter of this. That the fertility of the soil is not destroyed by irrigation is shown by the fact that areas first watered 17 years ago are still under cultivation: nevertheless it is evidently desirable to detect, measure and control any immediate or cumulative change in the soil that may result from this change in the conditions to which it is subject. A first step in this direction is to ascertain the normal state of the soil, and this paper will accordingly describe in some detail the soil profile of the area now under irrigation and the way in which compactness of profile is related to fertility. Reference will also be made to the origin of this soil and to the influences of which the soil profile is the product.

I. Vertical Distribution of Salts in the Soil.

(*a*) *Reliability of the method and interpretation of results.*

In this laboratory the salt content of soil is estimated by the conductivity method as described by Joseph (1). As many as six samples a minute can be examined by a practised operator and the method is therefore admirably suited for the very extensive investigations involved in alkali studies. That the method is not so arbitrary as it seems at first sight was shown by Hoagland, Martin and Stewart (3) who state that, though a 5 to 1 soil extract removes more material than is present in the soil solution, variations in the extract and in the soil solution are concordant. It will be shown below that two objections that might be made to the application of this method to Gezira soils may also be discounted. In the first place, although the soil sometimes contains considerable amounts of gypsum which, by reason of its low solubility, is not included in the estimate of salt content, the latter is very closely

related to the former in the sense that a soil with a high content of soluble salts also contains gypsum. The second difficulty arises from the necessity of condensing data. Thus, if the top 2 ft. of soil contain 0·1 per cent. sodium carbonate and the next 2 ft. contain 0·5 per cent. sodium sulphate, one has to say that the top 4 ft. have an average salt content of 0·3 per cent. At first sight it seems that important information is thus lost and that the average refers only to a part of the soil column and is therefore an arbitrary figure. It will be shown however that an average of this sort is a measure of compactness in the soil profile and that concordant results are obtained by the use of this and of other criteria.

(1) *Relation of soluble salt content to the occurrence of gypsum.* The samples handled in this laboratory fall for the most part into two groups: (1) those of lower salt content which contain no gypsum and yield sodium carbonate on extraction; (2) those of higher salt content which contain a large or small proportion of gypsum and yield sodium sulphate on extraction. A close relation exists therefore between the average salt content of a number of samples and the proportion which contain gypsum. Table 1 below shows for four groups of sample holes, representing an area known as the Northern Extension, (*a*) the average salt content of successive 6-inch steps, (*b*) the percentage occurrence of gypsum. The amount of gypsum was not estimated. Thus the figure 40 per cent. for group *W*, step 6, merely expresses the fact that 8 out of 20 samples were observed to contain gypsum.

Table I.

(Successive 6 in. layers.)

	Average salt contents				Occurrence of gypsum (%)			
Group ...	*W*	*X*	*Y*	*Z*	*W*	*X*	*Y*	*Z*
No. holes ...	20	20	20	17	20	20	20	17
Step 1	0·077	0·079	0·085	0·106	0	0	0	0
„ 2	0·088	0·098	0·117	0·121	0	0	0	0
„ 3	0·103	0·136	0·228	0·279	0	5	15	17
„ 4	0·147	0·249	0·440	0·670	0	20	55	76
„ 5	0·249	0·489	0·550	0·694	20	50	75	88
„ 6	0·314	0·536	0·542	0·651	40	85	80	82
„ 7	0·314	0·451	0·576	0·714	20	50	80	94
„ 8	0·290	0·423	0·545	0·658	20	40	70	88
„ 9	0·264	0·487	0·511	0·595	15	60	55	65
„ 10	0·294	0·463	0·487	0·540	21	65	63	65

Thirty pairs of salt contents and percentage occurrences of gypsum are contained in this table and it is found that they stand in very close correlation ($r = +0·957$). The average salt content X may be calcu-

lated from the percentage occurrences of gypsum Y by means of the equation

$$X = 0{\cdot}00562Y + 0{\cdot}158.$$

A different equation would be required to connect soluble salt content with the amount of gypsum present in a sample since the latter varies with depth in a way described later.

(2) *How are salt results to be summarised?* This question was answered by considering the distribution of salt with depth in the case of six groups of holes, whose salt curves when plotted against depth were alike in showing for the first 2 ft. low salt content and a slow increase with depth, for the second 2 ft. a rapid increase with depth and some falling off in the third 2 ft. Linear relations were found connecting

(1) the salt content at 24 in. depth,
(2) the salt content at 48 in. depth,
(3) the average salt content to 4 ft.,
and (4) the average salt content to 6 ft.

For comparison of the groups in respect to salt content these four criteria may be used indifferently whereas two other criteria,

(5) the average salt content to 2 ft.
and (6) the average salt content to 1 ft.,

cannot be used for comparative purposes since they agree neither with each other nor with the first four. The following table gives the actual data:

Table II.

Group	*C*	*A*	*D*	*E*	*B*	*F*
Salt content at 24 in.	096	102	127	148	159	187
Salt content at 48 in.	194	270	322	421	414	553
Average salts to 4 ft.	110	142	173	212	219	261
Average salts to 6 ft.	135	181	204	272	293	356
Average salts to 2 ft.	086	076	092	106	096	110
Average salts to 1 ft.	080	068	084	100	077	100

The table shows that in summarising salt results the depth to which averages are taken is immaterial provided that it is sufficient to include some high salt figures and so obliterate differences in the top 2 ft.

(*b*) *Vertical distribution of salts at the Gezira Research Farm and in the irrigated area.*

This subject is conveniently approached by considering first the distribution of gypsum. At a depth of 3 ft. small crystals of gypsum are readily observed in the soil of the Gezira Research Farm. At a

depth of 4 ft. no gypsum may be seen but at 4½ ft. lenticular crystals up to ¼ in. long are very conspicuous. The salt content rises suddenly at 3 ft. and then falls slightly with a second sharp rise at 4½ ft. In other words, gypsum seems to occur in two zones and the salt content has a sudden increase at the upper limit of these two zones. Concomitantly with the variation in salt content, there is a variation in alkalinity (pH) with depth and in physical properties of the soil as gauged by the rate of capillary rise[1]. This is shown in Table III below.

Table III.

(Successive 6 in. steps.)

Step ...	1	2	3	4	5	6	7	8	9	10	11	12
Salts %	0·07	0·08	0·09	0·11	0·16	0·43	0·49	0·43	0·54	0·65	0·65	0·61
Gypsum %	0	0	0	0	0	0·3	0·4	0 2	0·9	1·5	1·0	1·1
pH	9·44	9·51	9·53	9·59	9 49	9·10	8·89	9·14	8·95	8·76	8·74	8·81
Cap. rise	86	38	33	17	25	108	93	40	67	87	72	79

The main point to be made here is that with increasing depth there is a regular and well-defined series of changes in the character of the soil at the Gezira Research Farm. Examples follow of typical holes in other parts of the canalised area, all of which were sampled in successive 6-in. steps.

Table IV.

Example I. Bortobeil Left 7 *D:*

Step ...	1	2	3	4	5	6	7	8	9	10	11	12
Salts %	0·06	0·08	0·08	0·09	0·07	0·10	0·18	0·25	0·31	0·25	0 21	0·15
Gypsum %	0	0	0	0	0	0	0	0	0	0	0	0
Cap. rise	119	83	62	52	44	45	61	57	46	48	52	36

Table V.

Example II. Heweiwa East 65 *A:*

Step ...	1	2	3	4	5	6	7	8	9	10	11	12
Salts %	0·06	0·08	0·09	0·10	0·18	0·16	0·53	0·51	0·24	0·31	0·29	0·30
Gypsum %	0	0	0	0	0	0	0·6	0·6	0	0	0	0
Cap. rise	82	44	29	29	22	28	102	86	31	21	22	32

Table VI.

Example III. Abdel Daim West 24 *G:*

Step ...	1	2	3	4	5	6	7	8	9	10	11	12
Salts %	0·05	0·08	0·10	0·10	0·10	0·12	0·59	0·37	0·34	0·31	0·40	0·51
Gypsum %	0	0	0	0	0	0	0	0	0	0	0·6	2·2
Cap. rise	92	54	31	29	21	23	54	49	44	25	42	48

[1] Soil passing a 1 mm. sieve is transferred to tubes of 1 cm. diameter. These stand in a shallow tray to which water is added. The height to which water rises in 3 minutes and in 5 hours is measured; the difference is taken as the rate of capillary rise. We are indebted to Dr. E. M. Crowther of Rothamsted for suggesting this very convenient routine method.

Table VII.

Example IV. Abdel Hafiz West 7 I:

Step ...	1	2	3	4	5	6	7	8	9	10	11	12
Salts %	0·11	0·12	0·13	0·16	0·21	0·51	0·55	0·45	0·34	0·65	0·74	0·72
Gypsum %	0	0	0	0	0	0·1	0·4	0	0	1·7	5·3	5·9
Cap. rise	34	27	15	15	17	97	86	32	12	65	61	63

Table VIII.

Example V. Moharram 27 A:

Step ...	1	2	3	4	5	6	7	8	9	10	11	12
Salts %	0·06	0·08	0·09	0·10	0·13	0·48	0·38	0·34	0·31	0·40	0·47	0·40
Gypsum %	0	0	0	0	0	0·2	0·4	0·1	0·1	0·9	5·2	3·0
Cap. rise	54	36	19	24	18	79	69	39	20	51	56	59

Attention is drawn to the variation of soil character with depth. In Example I the salt content increases at steps 7, 8 and 9 and the rate of capillary rise increases at step 7. No gypsum was present. The increase in salt content is more marked in Example II where it coincides with an increase in the rate of capillary rise and with the appearance of gypsum.

Before considering Example III it should be noted that gypsum is estimated by washing soil on a 1 mm. sieve which retains only coarse crystals of this substance together with any nodules of calcium carbonate or large quartz grains that may be present in the sample. Small crystals of gypsum pass the sieve and so escape estimation. This occurred with step 7 of Example III. The presence of gypsum at this depth had been noted and the table shows an increase in salt content and in rate of capillary rise which confirm the observation. A second increase in both occurs at step 11 and this coincides with the appearance of a second zone of gypsum.

The occurrence of gypsum in two zones is clearly shown in Example IV and this distribution is confirmed by appropriate variations in content of soluble salts and in the rate of capillary rise. Example V is strikingly similar except that there is no break in the distribution of gypsum, in which respect the soil resembles that of the Gezira Research Farm (Table III). This condition of the soil may be described by saying that gypsum occurs in two overlapping zones and that the salt content and rate of capillary rise increase sharply at the upper limits of these two zones.

The conditions responsible for the differences shown by these five examples will be considered below. Emphasis is here laid on their general similarity and on the progressive character of the differences noted in passing from Examples I to V. In Examples III, IV and V

a 6 ft. column of soil includes two zones of gypsum; in Example II only one. The soil profile is more compact in Examples III, IV and V than in Examples I and II. We shall see below that other indications support the idea that these soils have the same general profile but in various degrees of compactness.

II. FIELD OBSERVATIONS ON SOIL PROFILE.

(a) *Soil profile at the Gezira Research Farm.*

The following is a general description of the appearance of a 6 ft. column of soil at the Gezira Research Farm. The surface soil to a depth of 2 ft. is rather dark brown; below it there is a layer of grey soil penetrated by tongues of brown, as shown in Fig. 1, and below the grey layer the soil is yellow brown. The colour change from dark brown to grey and from grey to yellow brown is not so striking as the diagram suggests and does not come out well in photographs, but nevertheless can be followed by careful inspection. At a depth of about 2 ft. ill-defined lumps of grey soil are seen; they have apparently been detached from the grey layer by intrusions of brown surface soil. Of these grey lumps those nearer the surface frequently contain small white specks of calcium carbonate (drawn oval in the diagram) while those a little lower down frequently contain small crystals of gypsum (lozenges in the diagram). The latter characterise the upper limit of the grey layer. Its lower limit coincides with the occurrence of white crumbly aggregates of calcium carbonate about 1 in. in diameter. At the zone of greatest concentration these amount to about 3 per cent. by weight of the soil. Below the zone of crumbly aggregates crystals of gypsum are present in considerable amount. In the diagram these are represented by lozenges. Hard nodules of calcium carbonate are distributed throughout the soil column but are not readily seen while the soil is *in situ*; those occurring below the grey layer are white, those above it are grey owing to the presence of a black substance which is deposited towards the outer surface of the nodule and near the walls of cracks inside it. (I am indebted to Mr G. W. Grabham, O.B.E., Government Geologist, for this observation.)

(b) *Method of making and recording field observations.*

Owing to the strongly marked structural character of the Gezira soil, field observations form a valuable adjunct to laboratory work. The following method of marking field observations is rapid and has given informative results: Samples are taken in 6 in. steps and are numbered

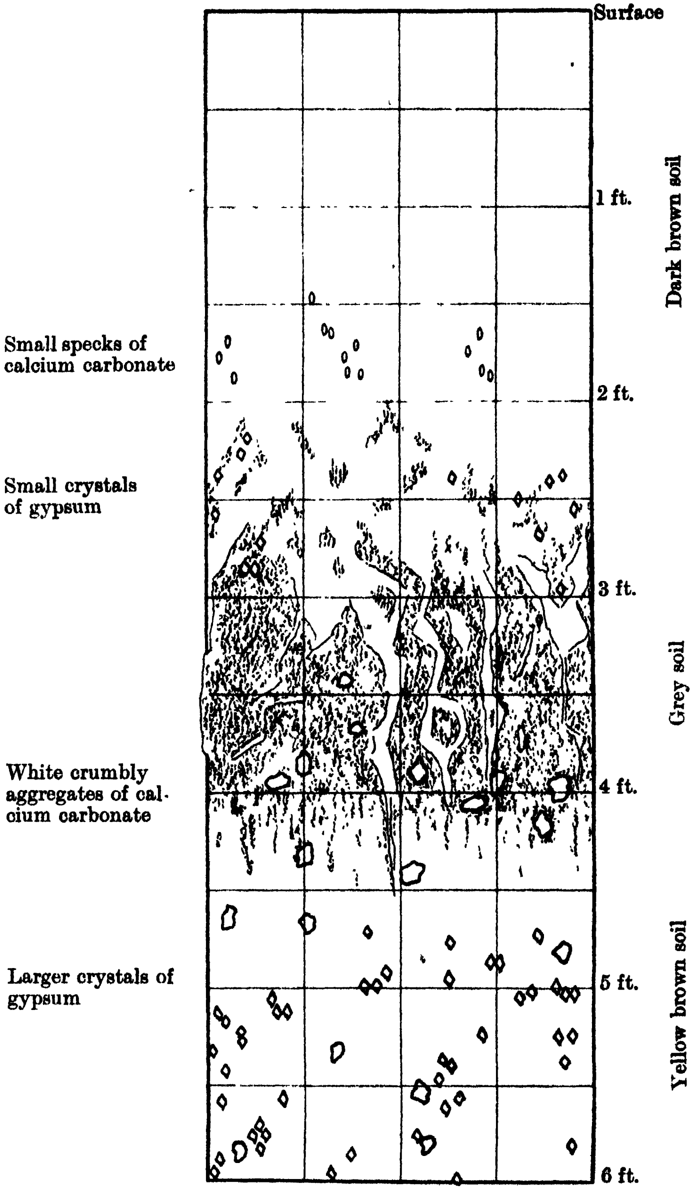


Fig. 1. Diagrammatic representation of soil profile at the Gezira Research Farm.

in succession from the surface. As each sample is taken it is examined and a note made as to its colour, content of gypsum and of white aggregates. Only rough grading is attempted: one or two crosses in the case of gypsum, one or two circles in the case of white aggregates. Other features of interest are recorded in a remarks column and the whole business adds very little to the time occupied in actually taking the samples.

Interest chiefly attaches to the depths at which changes in soil character occur. This varies from place to place so that when an area has been sampled by a number of holes some means of obtaining an average for the area is required. A simple way of doing this is to prepare a table with as many columns as there are sample holes and transcribe the field observations. The table is then a diagrammatic representation of the soil profile of the area. The next step is to count how many times a soil characteristic, such as grey colour, occurs at different depths. These numbers may conveniently be written at the side of the table and will show the distribution of that characteristic with depth. For example, in the case of an area of about 200 square miles sampled by 122 holes the occurrences of grey soil rose from 20 at step 4 to 112 at step 8 and fell to 48 at step 12. The mean and standard deviation of the distribution may then be calculated. Alternatively one may note for each hole the upper and lower limit of the grey zone and so obtain its mean depth and width.

(c) *Variation in compactness of the soil profile: comparison of soil of the irrigated area with that of the Gezira Research Farm.*

The main point established by the studies mentioned above is that when two areas differ in respect to the depth distribution of one soil characteristic they differ also in respect to that of other soil characteristics. In the following table the two last columns give the mean depth in inches of grey soil and of white aggregates of calcium carbonate for four groups of sample holes. At the Gezira Research Farm means of both characteristics are nearer the surface than in the irrigated area as a whole. It will be readily understood that this corresponds to a difference in salt content since where the soil profile is compact a 4 ft. column will include more salty subsoil than where the profile is disperse.

As a rule, when grey soil occurs near the surface its content of soluble salts and of gypsum is notably high. This is shown by Table I in which Groups *W* and *X* correspond to Group 3 of Table IX and Groups *Y* and *Z* correspond to Group 4 of Table IX. We thus obtain a fairly clear physical

view of the conditiɔn described as compactness of soil profile. A soil has a compact profile when its various zones lie near the surface and when the concentration of salts in the zones is markedly high. In this sense the soil of the Gezira Research Farm is more compact than that of the irrigated area and less compact than that of the Northern Extension.

Table IX.

Mean depth in inches of grey soil and of white aggregates.

Group	Area	No. of holes	Av. salts 1 to 4 ft.	Grey soil	White aggregates
1	Irrigated area	60	0·195	47	58
2	Gezira Research Farm	64	0·221	43	51
3	Northern Extension	40	0·253	38	42
4	,,	37	0·432	33	37

III. Relation of Compactness of Soil Profile to Fertility.

Joseph (1) found no evidence of qualitative difference in the alkali of good and bad plots and showed that yield (lb. cotton lint per acre) was related to salt content (percentage on the first 4 ft. of soil). The following is an abstract of his results:

48 good plots yield 606 salts 0·137,
48 bad plots yield 335 salts 0·190.

Additional data are given below. To reduce seasonal and local effects the yield of each plot was expressed as a percentage of the average yield for that season of the block (a unit of about 25 square miles) in which it lay.

Table X.

		Good plots			Bad plots		
Block	Season	No. of plots examined	Yield	Salts	No. of plots examined	Yield	Salts
7	1924–25	9	147	0·140	5	58	0·196
9	,,	8	153	0·144	8	70	0·186
4	,,		121	0·199	8	71	0·203
5	1925–26	13	115	0·168	8	50	0·221
6	,,	9	141	0·145	10	49	0·222
10	,,	10	119	0·189	9	41	0·155
11	,,	16	106	0·156	4	52	0·146

Salts and yields in this case give a negative correlation coefficient of 0·73. A similar relation exists between content of gypsum and yield of cotton and this is presumptive evidence of a relation between compactness of profile and fertility. Further evidence was obtained by so arranging the data as to restrict comparison to plots of equal average salt content and then looking for difference in the distribution of salts

and of gypsum. Salts and gypsum lay nearer the surface in bad plots than in good. So also in respect to depth of grey soil: the mean lay at 45 in. depth in the bad plots and at 48 in. depth in the good plots. For white aggregates of calcium carbonate the difference was small but in the same direction.

It is therefore proved (*a*) that high average salts are associated with low fertility, (*b*) that when the effect of this factor is cancelled the nearness of salts to the surface is associated with low fertility. This is summed up by saying that compactness of soil profile is associated with low fertility.

Now sodium sulphate is not very toxic to plants, gypsum is beneficial and it may be supposed that greyness of the subsoil is entirely without effect on plant growth. These factors are indications of adverse conditions and not causes of low fertility. The direct and major cause of low fertility is low permeability of the surface soil. This is shown either by comparing good plots with bad as in Table X or by cancelling the average salt effect and then making a comparison. In both cases there is a marked difference in the rate of capillary rise showing that water moves more freely in good soil than in bad. Investigations (1) have shown that permeability is largely dependent on the amount of sodium in chemical combination with the clay and this lends great probability to the view that where the soil profile is compact not only is there greater concentration of subsoil salts but also a greater concentration of sodium in chemical combination with the clay of the surface soil. The latter is directly related to permeability and thence to fertility. The general correctness of this view has been shown by field experiments on permeability already described (2).

IV. ORIGIN OF THE GEZIRA SOIL.

Observations as to the nature and distribution of soil salts harmonise well with the view of Mr G. W. Grabham, that the sandy subsoil of this almost featureless plain was laid down by a deltaic river. Seepage and evaporation at some distance from the main channels gave rise to salty deposits and fine wind-blown material accumulated on top of this forming a layer of heavy clay whose depth, determined by vegetation following rainfall, increases from north to south.

The climatic conditions to which the soil is now subject are briefly as follows: in July and August the Gezira receives two-thirds of its annual rainfall and within this period the uptake of water is about

1000 tons per acre. Owing to the heavy nature of the soil most of this water is held near the surface and suffices for the quickly maturing grain crop which is sown in slight depressions of the plain. The natural vegetation is sparse thorn scrub. For about nine months of the year there is no rain and the soil rapidly dries out from the surface, shrinking and developing cracks which are wide or narrow according as the soil has more or less water to lose. In April, May and June the intense insolation and heating of the surface soil set up wind eddies which lift and transport loose material. Part of this finds its way into cracks and in the early June rains more surface soil is carried down so that the position of the cracks may subsequently be inferred from tongues of brown soil which penetrate the grey layer (see Fig. 1). In this way some grey soil is brought nearer to the surface and a process of soil circulation is set up. Mr Grabham attributes more deep-seated displacements to the alternation of longer periods in which light and heavy rain seasons predominate. These displacements produce cleavage surfaces running at an angle of some 30 degrees to the horizon and occurring in the brown soil which underlies the grey.

In spite of this mixing process the soil maintains a well-marked profile. This must be due to readjustment which like the mixing is more thorough near the surface than below. It may be presumed that whereas drought and the early rains tend to break up the profile the later rains tend to restore it. Thus when a lump of grey soil is first detached from the grey layer it may contain small crystals of gypsum. Sodium sulphate is also present so that the crystals are isolated from the more alkaline brown soil which surrounds the lump. Later on the protecting sodium sulphate is displaced downwards and the crystals are then converted to small specks of calcium carbonate by contact with a more alkaline medium.

It seems likely moreover that the original saline constituents of the soil were hard white nodules of calcium carbonate formed within the soil column and sodium sulphate formed at the surface. The latter reacting with wind-blown material would enrich it in sodium and be converted to calcium sulphate. High original content of sodium sulphate and of nodules would thus be associated with high subsequent content of gypsum, high concentration of sodium in combination with the clay and high content of nodules. These characteristics do in fact occur together in less fertile soil and it is therefore probable that they have a common cause in the original distribution of sodium sulphate, that is, in the original localisation of seepage.

Sodium sulphate now occurs in the grey soil which receives only a small part of the annual rainfall. Loss of water by drying is correspondingly slow in this zone and throughout the year it has a higher average moisture content than the soil above or below it. Wilsdon (5) showed that water moved from soil of lower to soil of higher salt content; it is conceivable that the reverse process occurs in the Gezira and that the sodium sulphate moves from a region of lower moisture content to a region of higher moisture content. Direct displacement of sodium sulphate from the surface soil would also tend to maintain its present distribution.

The origin of white crumbly aggregates of calcium carbonate is not clear. At the Gezira Research Farm they sometimes enclose large crystals of gypsum. It is possible therefore that carbonate dissolved from the upper layers is precipitated at the bottom of the grey layer. On the other hand, in other areas the aggregates have the appearance of partially disintegrated white nodules. The latter during their slow upward journey through the soil pass through regions of different alkalinity (see Table III). As stated above, the grey colour of nodules occurring in and above the grey layer is due to separation of a black substance towards the outer surface and near the walls of cracks within the nodule. Some reaction undoubtedly takes place and it is perhaps significant that the zone of crumbly white aggregates corresponds to a minimum in the distribution of hard nodules. The grey nodules decrease in amount from the surface to the bottom of the grey layer while the white nodules increase in amount from the bottom of the grey layer to the foot of a 6 ft. column.

An account will shortly be given as to changes in salt distribution consequent on irrigation and fallowing. Changes brought about by heavy flooding are also under investigation and it is hoped that these studies will lead to a clearer view as to the genesis and continued regeneration of the soil profile.

SUMMARY.

The distribution of salts in the soil is generally related to compactness of the soil profile as judged by the distribution of gypsum, of calcium carbonate aggregates and of soil colour. The relation already established between salt content and fertility is now expressed as a relation between compactness of profile and fertility. The data agree well with geological views as to the origin of this soil. Influences of which the soil profile is the product are also discussed.

I am much indebted to Mr G. W. Grabham for practical instruction in field work and for information as to the origin of Gezira soil. I wish also to thank Dr A. F. Joseph for his interest in this work and for facilities placed at my disposal.

REFERENCES.

(1) Joseph, A. F. (1925). *J. Agric. Sci.* **15**, 407–419.

(2) Greene, H. (1928). *Ibid.* **18**, 531–543.

(3) Hoagland, Martin and Stewart (1921). *J. Agric. Res.* **20**, 381–395.

(4) Joseph, A. F. *Report of the Sudan Govt. Chemist for 1927.*

(5) Wilsdon, B. H. (1921). *Memoirs Dept. of Agric., India* (Chemical Series), **6**, No. 3.

(*Received March 6th*, 1928.)

SOIL PERMEABILITY IN THE EASTERN GEZIRA.

By H. GREENE.

(Wellcome Tropical Research Laboratories, Wad Medani, Sudan.)

(With Five Text-figures.)

The Sennar dam was completed in July 1925. Of the area it commands about a tenth was then brought under irrigation; this stretches 50 miles along the west bank of the Blue Nile and averages 10 miles in width. Joseph (1) has described the mechanical composition (upper 4 ft. 50 to 60 per cent. clay), salt content (upper 4 ft. 0·2 per cent.) and alkalinity of the soil and the quality of the irrigation water. The following table outlines the climatic conditions (2) at Wad Medani (14° 24′ N., 33° 31′ E.) for the period 1902-1920, and shows also the system of crop rotation.

Table I.

	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Max. temp. ° C.	41·9	40·0	36·6	35·1	36·7	38·9	37·3	34·1	33·8	35·3	38·3	41·1
Min. temp. ° C.	23·6	23·3	22·2	21·2	21·7	22·0	20·0	16·1	15·0	15·8	18·3	21·2
Rel. humidity (*a*)	24	40	58	66	58	43	33	33	34	26	20	18
Evaporation (*b*)	17·2	14·0	9·8	7·0	8·5	11·0	14·0	12·8	12·6	15·0	17·2	18·8
Rainfall (mm.)	13	42	113	148	67	14	1	0	0	0	0	2
Main crop	Fallow			Long staple Egyptian cotton								
Second course	Fallow			Half grain (*c*) / Half forage (*d*)					Fallow			
Third course				Fallow								

(*a*) Per cent.; (*b*) mm. per day, Piché; (*c*) Sorghum Vulgare; (*d*) Dolichos lablab.

It will be seen that two-thirds of the annual rainfall occurs in the months of July and August, and that crops are sown towards the end of the rain season.

The present paper deals with three years' study of field moisture content. If the results, which are expressed as per cent. by weight on the dry soil, are considered in relation to water economy and control, they may be converted to tons per acre by assuming that a 6 ft. acre of dry soil weighs 10,000 tons. From the agricultural point of view it is desirable to ascertain not so much the total amount of water present but the amount readily available for Egyptian cotton under local climatic conditions of high temperature and low humidity. The following table may serve as a rough guide to the interpretation of the field data. Except in the case of moisture equivalent and hygroscopic coefficient the constants shown were either determined in this laboratory or inferred from measurements of moisture content in the field.

Table II.

Moisture content (%)	Condition of soil
Over 60	Maximum water holding capacity (*a*)
Over 40	Maximum for healthy growth
About 40	Moisture equivalent (*b*)
36 to 40	Optimum for plant growth
About 30	Cotton begins to need watering
About 28	Lento capillary point (*c*) lower limit of readily available water
23 to 24	Cotton suffers severe check; crop ruined
18 to 20	Wilting point for cotton seedlings in pots
About 14	Hygroscopic coefficient
6 to 8	Soil in equilibrium with air of 25 per cent. relative humidity

(*a*) Brass box method, Keen and Raczkowski, *Journ. Agric. Sci.* **11**, pt 4 (1921). (*b*) Briggs and McLane, *U.S. Bureau of Soils Bull.* **45** (1907); Joseph and Martin, *Journ. Agric. Sci.* **13**, pt 1 (1923). (*c*) Widtsoe and McLaughlin, *Utah Agric. Coll. Bull.* **115** (1912).

It appears from this that the object of irrigation should be to maintain a sufficient depth of soil at a moisture content between 30 and 40 per cent. Experiment showed that although the soil has a high water holding capacity, its permeability is low, so that at the Gezira Research Farm no considerable part of rain water or of irrigation water penetrates below a depth of 3 ft. while the bulk of it is held up in the top 2 ft. to which region root development is largely restricted. The depth of penetration is not constant throughout the irrigated area: in more permeable soil, root development, plant growth and yield of lint are increased, and in less permeable soil are diminished. Observations (1) on the relation of soil salts to cotton yield have been supplemented by extensive field studies which have established that different parts of the irrigated area show the same general profile but differ in respect to the depth of soil within which the sequence of soil zones is manifest. Where the profile is compact, salt content is high, permeability low and yield small; with an extended profile, salts are low, permeability better and yield good. Work on soil profile will form the subject of a separate communication; the present paper is divided as follows:

I. Depth of penetration of water at or near the Gezira Research Farm.
   (*a*) Changes of moisture content in land under native cultivation.
   (*b*) Changes in moisture content of land under irrigation.

II. Testing permeability in the field.
   (*a*) The dependence of plant growth on permeability of the soil.
   (*b*) The use of 14 days' flooding as a test of permeability.

III. The use of gypsum to increase permeability of the soil.

I. DEPTH OF PENETRATION OF WATER AT OR NEAR THE GEZIRA RESEARCH FARM, WAD MEDANI.

This laboratory is situated at the Gezira Research Farm which was started in 1918. Data as to the soil are given by Joseph (*loc. cit.*). For the last two years soil samples have been taken in 6 in. steps to a depth

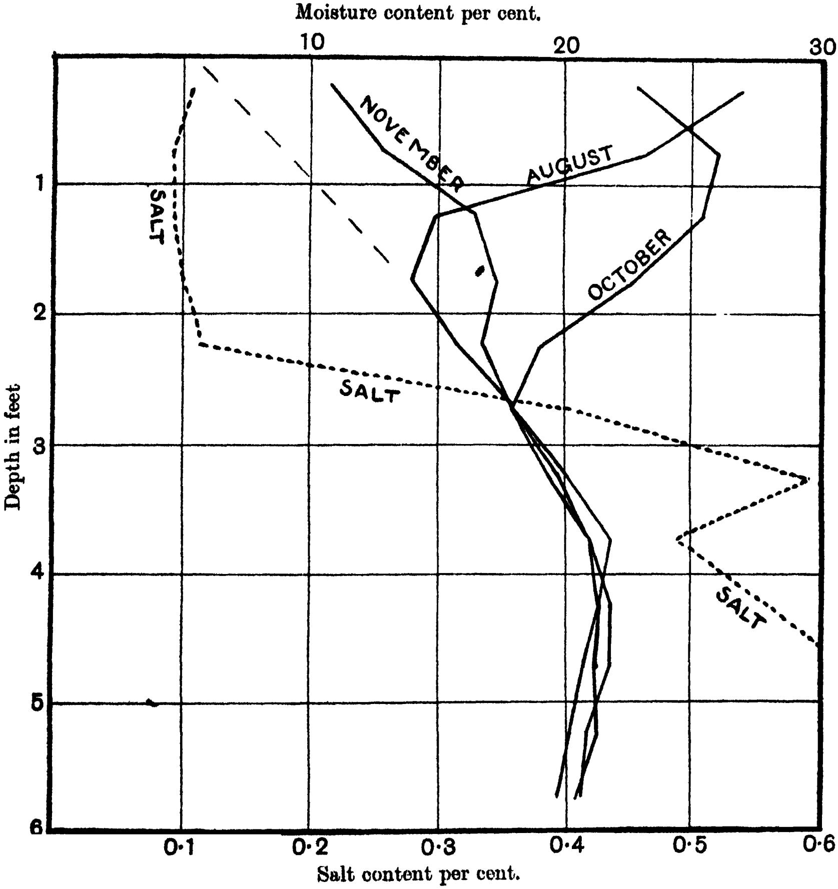


Diagram I. Moisture content of land under native cultivation.

of 6 ft. by means of a boring apparatus which is separately described (3), without which certain investigations reported here would have been almost impracticable. As a rule results for moisture content given in this paper are the averages of determinations based on samples taken from at least eight holes.

(a) *Changes of moisture content in land under native cultivation.*

Under native cultivation (4), light earth banks direct rain water to selected areas which receive no preliminary cultivation and are heavily cracked as a result of water loss during the preceding dry season. After sowing the land is kept clear of weeds and the crop (sorghum) rapidly matures. The changes in moisture content which occur under these conditions are shown in Diagram I. At first only the top foot receives a considerable increase in moisture content; with continued rain penetration extends to 3 ft. and thereafter the soil rapidly returns to the moisture distribution characteristic of fallow land. The salt content of successive 6 in. steps is shown in the diagram by a dotted line. It will be noted that the first sharp rise in salt content occurs at the limit of rain penetration.

(b) *Changes in moisture content of land under irrigation.*

Some representative experimental plots were sampled towards the end of the rain season and after the first artificial watering. The results are given in Table III together with figures for a group of plots which were sampled when they had received no water for a period of eight months. It is evident from these figures that different plots show a fairly uniform response to rains and first watering, and that penetration is again limited to 3 ft. It will, however, be noticed that the moisture content of the lower 3 ft. is higher than that of land under native cultivation. The difference may reasonably be ascribed to very slow translocation of water occurring during previous seasons of irrigation and it will accordingly be supposed that some small fraction of irrigation water will eventually find its way to the ground water level which, in the Gezira, is 60 ft. below.

Table III.

Moisture content of successive 6 in. steps.

Step	1	2	3	4	5	6	7	8	9	10	11	12
Plot 4	32·3	35·1	32·9	29·3	23·8	21·8	22·6	23·5	24·4	25·1	25·3	24·5
Plots 10 and 18	32·4	35·3	32·1	25·8	21·4	21·2	21·8	23·2	23·8	23·4	21·2	21·3
Plot 28	28·8	32·6	30·7	26·2	22·4	21·7	23·2	23·5	24·5	24·1	23·4	22·8
Mean	31·2	34·2	31·9	27·1	22·5	21·6	22·5	23·4	24·2	24·2	23·3	22·9
Fallow plots	7·4	10·8	15·6	17·5	20·1	21·3	22·9	23·6	23·6	23·4	22·2	21·6

Plot 4: continuous cotton ninth season; Plots 10 and 18: rotation cotton; Plot 28: cotton, gypsum with and without sulphate of ammonia.

Several attempts have been made to determine the course and extent of changes that occur on irrigation and during the 15 or 20 days that elapse between one irrigation and the next.

Diagram II shows the moisture content of a plot 24 hours before and 24 hours after an irrigation which was estimated at 430 tons to the acre. Two days later, the second foot had gained a little in moisture at the expense of the first, whereas the bottom 3 ft. remained constant throughout the irrigation cycle. This behaviour on irrigation is characteristic of Gezira Research Farm soil.

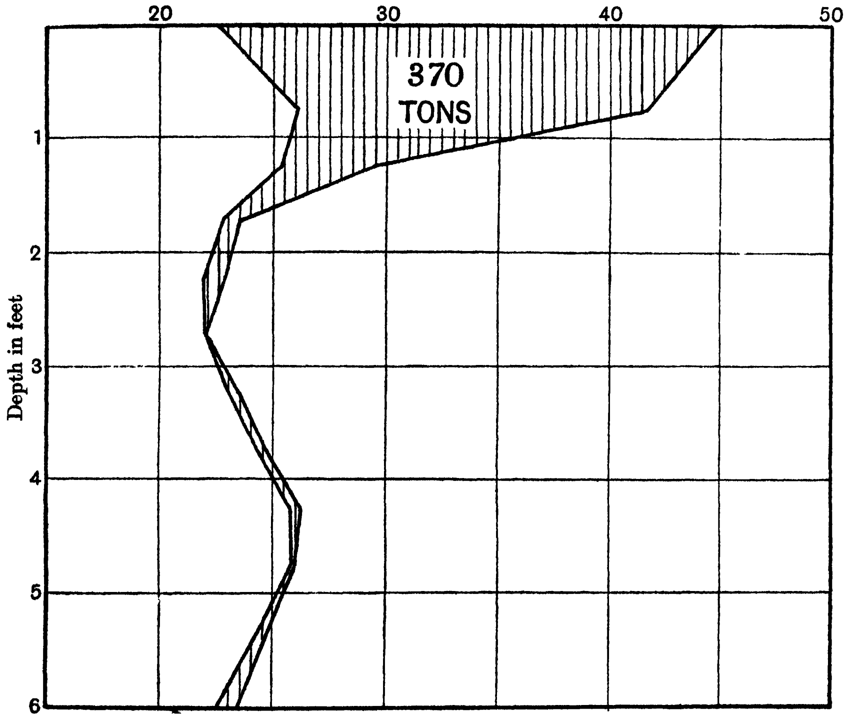


Diagram II. Moisture content of a cotton plot at the Gezira Research Farm 24 hours before and 24 hours after a watering estimated at 430 tons per acre.

II. TESTING PERMEABILITY IN THE FIELD.

(*a*) *The dependence of plant growth on permeability of the soil.*

In the Gezira cotton is watered at intervals which vary from 15 to 20 days according to time of year. The amount of water applied also varies but 400 tons per acre (roughly 4 in. depth) is about the average. The object of field tests of permeability is to ascertain how effectively the soil can store water for the use of plants under these conditions. As loss by deep percolation is slight, efficiency of storage largely depends on the ratio of water transpired by the crop to water lost by direct

evaporation. This ratio is by no means easy to determine. At the farm in October 1926, a plot growing vigorous cotton was losing water at the rate of 32 tons per acre per day: at the same time closely adjoining land which had been heavily flooded but bore no crop lost water at the rate of 9 tons per acre per day. On this basis loss by transpiration was 23 tons per acre per day or 70 per cent. of the total loss. For cotton in Egypt, Balls (5) found loss by transpiration to be of this magnitude and was surprised to find his results in agreement with the previous work of M. Audebeau (5). If then this estimate is approximately correct it follows that in the course of a cotton season the crop transpires some 4200 tons of water per acre. The weight per acre of dry matter above ground is about 3 tons (Joseph (6)), so that the water requirement of cotton in the Gezira is about three times that of ordinary crop plants as given by Briggs and Shantz (7). Under such conditions the danger of water strain is obviously acute and it will be readily understood that where the soil is so impermeable that only the surface is affected by irrigation, loss by direct evaporation is much increased with the result that towards the end of each irrigation cycle the crop suffers from drought. An instance follows of the dependence of yield on permeability. Samples were taken from two cotton fields, one bearing a vigorous and the other a stunted crop. In the good field water had penetrated 4½ ft., whereas in the other below 1½ ft. the soil was hard and dry to the touch. Exposure of cotton roots showed that their development extended to 5 ft. in the good soil and to little over a foot in the bad soil. The salt content of the two fields is given below; it will be noted that in the bad soil salts are present in greater amount and are nearer to the surface than in the good soil, in other words, the salt profile is more compact.

Table IV. *Salt content of successive foot samples in good and bad soil.*

Estimated by conductivity of 5 to 1 water extract (percentages).

Foot ...	1	2	3	4	5	6
Good soil	0·071	0·092	0·105	0·256	0·212	0·147
Bad soil	0·104	0·137	0·395	0·651	0·548	0·520

This brief discussion indicates the value of field permeability trials as a test of fertility.

(*b*) *The use of* 14 *days' flooding as a test of permeability.*

The main reason for not attempting to test permeability by means of a single comparatively light watering is that the difference in soil moisture content so caused is difficult to measure owing to local varia-

tions of the soil. For example, when a plot was sampled by 16 bore-holes, spaced some 20 yards apart, before and again after watering, it was found that the estimate of uptake was liable to considerable error. Single estimates of uptake for the first foot varied from 2·0 to 18·2 per cent. (33 to 300 tons per acre). For 16 estimates the means and standard deviations were:

First foot:	Mean + 10·4 per cent.	S.D. 4·0 per cent.
Second foot:	Mean + 3·0 per cent.	S.D. 5·4 per cent.
Third foot:	Mean − 0·3 per cent.	S.D. 1·9 per cent.

Thus in spite of the level nature of the soil, and its general low permeability, the distribution of water was very uneven, although it was not liable to systematic variation such as occurs on sloping ground or on permeable soil where the arrangement of distributing channels is of great importance. Replicated experiments on small squares (1/50 acre) have shown that heavy flooding gives satisfactorily concordant results.

That small differences in preliminary cultivation of fallow soil do not greatly affect the depth of penetration, when flooding lasts for 14 days, was shown by squares which had received the following treatments:

1. Early ridging (November 1925).
2. Late ridging (July 1926).
3. Bastard trenching to a depth of 3 ft.
4. Two waterings (October and December 1925).
5. No treatment.

The squares were flooded in August 1926 and sampled a month later. The moisture results were:

Table V.

(Percentages.)

Foot ...	1	2	3	4	5	6
Treatment 1	25·0	32·0	30·8	27·9	23·8	22·3
„ 2	25·5	33·0	31·6	30·0	29·2	23·0
„ 3	24·1	30·5	34·3	33·1	34·0	30·7
„ 4	23·3	33·3	32·3	30·0	29·0	24·1
„ 5	21·3	32·8	31·2	29·5	26·6	22·6

Thus, with the exception of treatment 3, there was not much to choose between the various squares. Cotton was sown on these squares and two interesting observations were made. The young plants went 6 weeks without further watering, whereas fortnightly waterings are usually required. Root development extended below 5 ft. in treatment 3, whereas, in this soil, it is usually restricted to 2 ft. This showed that

the salt content of the third and fourth foot (about 0·5 per cent.) is not of itself an obstacle to plant growth.

The effect of varying the time of flooding on uptake of water was examined, and Table VI gives an abstract of the results.

Table VI. *Moisture content per cent.*

Foot	Before flooding	3 days	Uptake	14 days	Uptake
1	13·8	35·6	21·8	33·5	19·7
2	17·9	32·2	14·3	33·4	15·5
3	18·8	26·0	7·2	32·0	13·2
4	21·6	23·1	1·5	26·2	4·6
5	22·2	22·2	0·0	22·0	−0·2
6	21·3	21·4	0·1	21·1	−0·2

No advantage would be expected from lengthening the time of flooding.

The rate of drying out after flooding has been investigated with results which are shown in Diagram III. The figures by the four upper curves give the number of days between the end of flooding and the time of sampling. For the first four months after flooding, loss of water by drying was confined to the top 4 ft. of soil and the amount lost through that period diminishes from the surface downwards; thereafter a fairly uniform loss occurs throughout a 6 ft. column. Dr E. M. Crowther, of Rothamsted Experimental Station, who spent some five months in this laboratory, ascertained that the soil has maximum density at a depth of 33 in. This presumably corresponds with the inflection shown by the curves at that depth.

The results shown in Diagram III form part of another investigation; for our present purpose it is sufficient to note that, although loss of water from the surface is very rapid, movement of sub-soil water after cessation of flooding is very slow, so that if samples are taken as soon as the surface has dried, they will indicate with sufficient accuracy the depth of soil affected by flooding.

In the introduction to this paper, it was stated that compactness of soil profile is associated with low fertility. Compactness is gauged in the field by examination of freshly drawn samples for colour, content of gypsum crystals and of calcium carbonate; in the laboratory the distribution of soluble salts with depth and the rate of capillary rise for successive samples is studied from the same point of view. Consideration of the relation of salt content to fertility led to the inference that where the profile was compact permeability would be low. A field test on this point was carried out at two places about 30 miles north of

Wad Medani for which field and laboratory observations indicated a marked difference in compactness of soil profile. This difference is shown in the first two columns of Table VII: these give the salt content of successive 6 in. samples while the remainder of the table shows changes in moisture content caused by 14 days' flooding. The experiments were conducted at Abu Ushar, where the soil was judged to be of good quality, and at Ganib, where the soil was judged to be of bad quality.

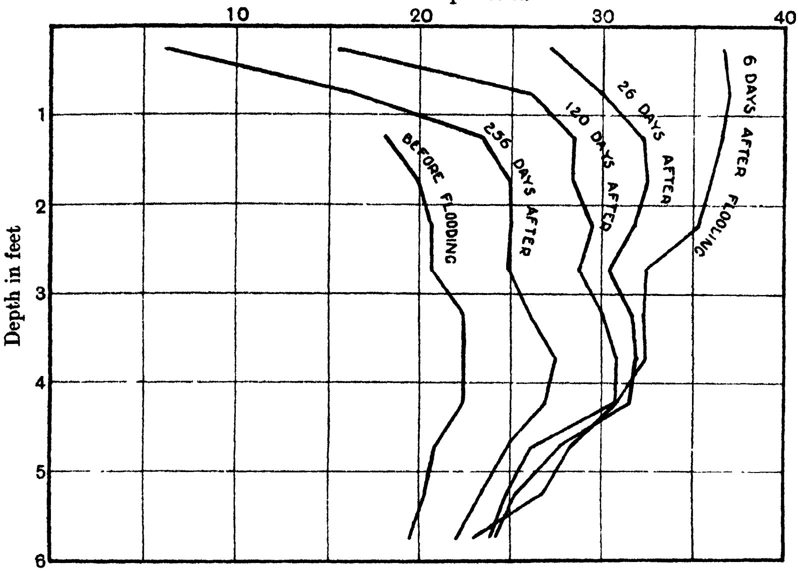


Diagram III. Drying out of land after 14 days' flooding.

Table VII.

Step	Salt content (%) Good soil	Salt content (%) Bad soil	Moisture content (%) Good soil: Before flooding	After flooding	Uptake	Moisture content (%) Bad soil: Before flooding	After flooding	Uptake
1	0·088	0·107	12·7	33·6	20·9	4·9	29·0	24·1
2	0·095	0·133	13·3	37·7	24·4	8·5	33·1	24·6
3	0·111	0·704	12·5	39·5	27·0	8·1	18·6	10·5
4	0·171	0·601	14·9	39·4	24·5	12·2	13·7	1·5
5	0·404	0·441	16·0	39·0	23·0	13·7	14·2	0·5
6	0·440	0·477	16·9	37·9	21·0	13·5	13·9	0·4
7	0·428	0·666	16·7	34·8	18·1	13·3	13·8	0·5
8	0·319	0·612	16·4	33·5	17·1	13·1	13·6	0·5
9	0·250	0·633	15·4	32·5	17·1	13·1	13·5	0·4
10	0·235	0·598	15·3	30·1	14·8	12·7	13·7	1·0
11	0·255	0·582	14·7	26·8	12·1	13·4	13·0	−0·4
12	0·264	—	14·6	18·0	3·4	13·3	12·2	−1·1

The striking difference of permeability shown by these two soils thus amply confirms the conclusions indicated above.

III. The use of Gypsum to increase Permeability of the Soil.

The fact that Gezira soil is alkaline and that material extracted by water from surface soil is mostly sodium carbonate, suggests that the low permeability of the soil is due to the amount of sodium which is in chemical combination with the clay. Other bases, notably potassium and calcium, are similarly combined, but work in the Wellcome Tropical Research Laboratories (9) Khartoum has shown that their presence improves the physical properties of the clay. In so far as the proportion of sodium to calcium is concerned, this dependence of physical properties on composition has been generally recognised and reference to individual workers in this field is perhaps unnecessary. The use of gypsum as a soil corrective is also firmly established largely owing to the work of Hilgard and his associates, and was recommended for this area by Beam (8) 17 years ago. Early trials did not give very marked results in favour of gypsum and it may be supposed that the system of watering used in conjunction with this treatment was not quite suitable or that some other factor such as shortage of nitrogen imposed a limit to plant growth. The recent trials have, however, shown that Beam's recommendation was well founded, and experiments made here strongly confirm it. This work, which is described below, is of additional interest in relation to the genesis of this soil. Although a high salt content is taken to indicate low permeability the salts mainly consist of sodium sulphate and the soil contains in addition crystals of gypsum which by reason of their low solubility are not dissolved in the course of a five to one extraction, but which nevertheless sometimes occur in considerable amount. The second foot of soil at Ganib for example contains much gypsum in addition to the soluble salts shown in Table VII. To what can impermeability of this soil be attributed? There is reason to suppose that salts present in the soil were originally derived by evaporation of river water (1) to give calcium carbonate and sodium sulphate. The latter reacting with the wind-blown material of which the upper soil is composed, enriched it in sodium and was converted to calcium sulphate. The arrangement of these components in a definite profile is in some way due to the long continued alternation of rains and dry seasons and the immediate factor in maintaining this distribution is probably the depth at which the highest average moisture content occurs. At the Gezira Research Farm this depth is about 4 ft. (see Diagram I) and the

salts may move to this region under the influence of osmotic pressure. The course of these changes is not fully understood, but since high salt content of the subsoil is associated with low permeability of the surface soil, there is some reason for connecting both with a common factor. The opinion advocated above is that this common factor is the amount of sodium sulphate originally deposited by river water and that the mode of its action is by base exchange substituting sodium for calcium in the soil and so affecting its physical characteristics. A more detailed

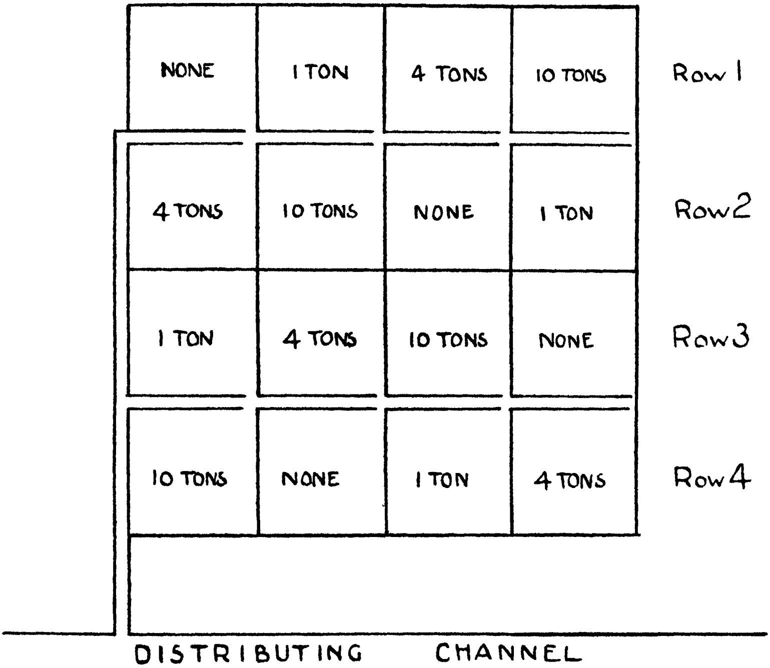


Diagram IV. Layout of an experiment to test effect of gypsum on soil of low permeability.

account of observations bearing on this point will be presented later, but the present brief discussion may help to explain the apparent anomaly of applying gypsum to a soil which (*a*) does not contain a high percentage of sodium carbonate, and (*b*) already contains considerable amounts of gypsum.

The use of gypsum in conjunction with heavy watering enabled the soil of the Gezira Research Farm to take up increased amounts of water. A detailed account of these experiments is, however, of less interest than corresponding results obtained at Ganib where the experiment described

in the preceding section had disclosed a high degree of impermeability. The layout of this experiment, which is given in Diagram IV, is of interest as showing what liberties can be taken with this soil since no allowance was made for interference between various treatments on very closely adjoining squares.

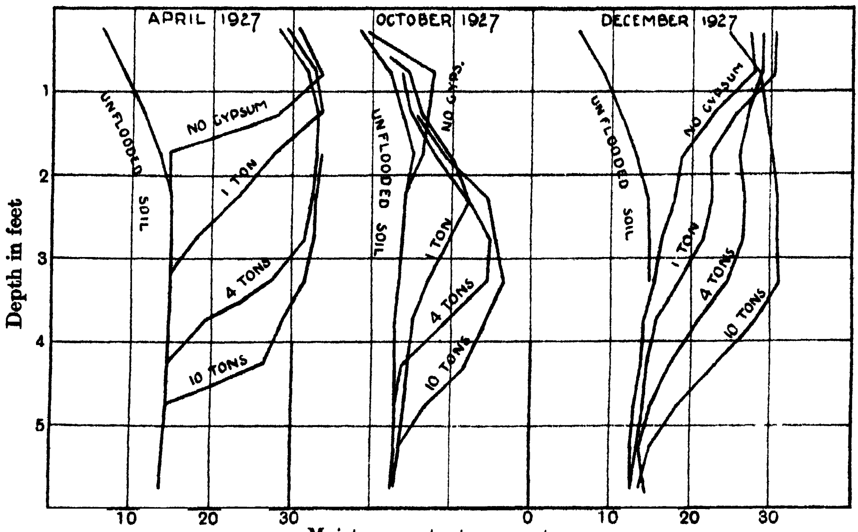


Diagram V. Effect of gypsum on permeability of soil.

The subplots (1/50 acre) were arranged in a compact block and received gypsum at the rate of none, 1 ton, 4 tons and 10 tons per acre. Each of the four rows was watered for 14 days in all, row 2 beginning two days after row 1 and so on. After flooding, the taking of samples was similarly spaced so that the time of drying was the same for all subplots, each of which was sampled twice. The results for separate treatments were in excellent agreement, and when averaged give the moisture distributions shown in Diagram V for April 1927. The same squares were sampled in October, that is, after a period of drying and in December after 10 days' flooding. It will be noted that in the nine months between April and December the boundary between wetted and unwetted soil had moved downwards about 6 in. and that there is complete absence of interference between treatments such as would result from lateral movement of subsoil water. It need hardly be said that this layout of a watering experiment is not recommended for general use.

SUMMARY.

An account is given of studies of moisture content in the field. The results are in agreement with Joseph's (1) view that the relation between salt content and fertility is chiefly due to the effect of sodium salts on soil texture. At the Gezira Research Farm a single watering moistens only the top 3 ft. of soil, although in the course of an irrigation season some small percolation continues below this depth. The water requirement of cotton in this region is extremely high and danger of water strain is correspondingly acute. The effect of 14 days' flooding is taken as a measure of permeability in the field and this test was applied with confirmatory results to two areas whose agricultural value had previously been gauged both by laboratory studies and by field observation of the soil profile. The genesis of the Gezira soil is briefly discussed with regard to the relation between salt content and fertility and with regard to the use of gypsum as a corrective. Marked improvements in permeability have been brought about by applications of this substance.

I am indebted to Dr A. F. Joseph, under whose direction this work was done, for his useful suggestions and for facilities placed at my disposal.

REFERENCES.

(1) JOSEPH, A. F. (1925). "Alkali Investigations in the Sudan." *Journ. Agric. Sci.* **15**, 407–419.

(2) *Climatological Normals for Egypt and the Sudan, Candia, Cyprus and Abyssinia.* Govt. Press, Cairo, 1922.

(3) GREENE, H. (1928). "A soil boring apparatus." *Journ. Agric. Sci.* **18**, 515–517.

(4) DAVIE, W. A. (1924). *The Cultivated Crops of the Sudan including Cotton.* Sudan Govt. Dept. of Agriculture and Forests.

(5) BALLS, W. L. (1912–13). *Journ. Agric. Sci.* **5**, 469–482.

(6) JOSEPH, A. F. *Report of the Sudan Govt. Chemist for* 1920.

(7) BRIGGS, L. J. and SHANTZ, H. L. (1913). *U.S. Bureau Plant Ind. Bull.* **284**.

(8) BEAM, W. (1911). *Fourth Report of Wellcome Tropical Research Laboratories,* vol. B, 23–84.

(9) JOSEPH, A. F. *Report of the Sudan Govt. Chemist for* 1927.

(*Received March 6th,* 1928.)

THE COMPOSITION AND NUTRITIVE VALUE OF SUGAR BEET PULP.

By H. E. WOODMAN, M.A., Ph.D., D.Sc. and
W. E. CALTON, B.A.
(The Institute for the Study of Animal Nutrition, School of Agriculture, Cambridge University.)

Introduction.

Much of the farmer's interest in the newly-established beet sugar industry is centred on the value, from the feeding standpoint, of the various by-products which arise during the process of extraction of the sugar from the beets. The following data, taken from a summary compiled recently by the Ministry of Agriculture (1), afford an idea of the increasing amounts of such by-products which are becoming available for use on the farm as a result of the progress which has been made by the sugar industry in this country during the last three years.

Season	1925–1926 tons	1926–1927 tons
Tonnage of beet delivered to factories	431,185	1,117,072
Production of by-products:		
Pulp: Dry	21,795	62,800
Wet	31,481	26,138
Molasses	270,910 cwt.	715,886 cwt.

The total production of beet pulp, wet and dry, during the past four seasons in this country is shown in the following table (2):

	Production	
Season	Dry tons	Wet tons
1924–5	7,510	18,617
1925–6	21,795	31,481
1926–7	62,800	26,138
1927–8	88,000	18,000

The whole of the wet beet pulp is consumed in this country, mainly on account of transport considerations and keeping difficulties, by farmers in close proximity to the factories. Of the dried beet pulp, considerable quantities were exported in the season 1926–7, when English feeders were only beginning to realise its value as a feeding stuff. How

home consumption has increased in the present season, however, is shown below:

Season	Total dry pulp produced tons	Purchased for home use tons	Exported tons
1924–5	7,510	7,510	Nil
1925–6	21,795	17,138	4,657
1926–7	62,800	26,040	36,760
1927–8	88,000[1]	68,000[1]	20,000[1]

[1] Estimated figures.

The following comment on the foregoing figures is worth recording (2):

Experience in countries where sugar beet is regarded as a normal crop in the rotation shows that growers look upon the cheap supply of wet or dried pulp as the chief inducement to its cultivation. In England, where, in comparison with the Continental countries, the sugar beet industry is in its infancy, growers and others have been somewhat reluctant to purchase supplies freely until they were convinced of its feeding value. That its merits as a feeding stuff are now much more widely recognised is shown by the increased quantities purchased for home use.

OBJECTS OF PRESENT INVESTIGATION.

If, as appears probable, the growing of sugar beet is destined to become a permanent feature of British agriculture, it is necessary that sugar beet pulp should find a place in the recognised dietary of the farm animals of this country. Our present knowledge of the uses and nutritive properties of this feeding stuff, however, is based largely on the results of old German trials and of somewhat more recent experiments carried out in America. Reference to the conclusions which have been drawn from these foreign investigations will be made during the course of this communication.

Little or no experimental work on the feeding of sugar beet pulp has been carried out in this country up to the present time. For that reason, considerable doubt exists in the minds of both farmer and scientific man as to the actual nutritive value of this new feeding stuff. When seeking advice on this question, the farmer is usually instructed to regard beet pulp solely as a substitute for roots in the ration and to base the replacement on the assumption that 1 lb. of dried beet pulp is equivalent to 7–8 lbs. of mangolds. The possibility of being able to look on dried beet pulp as a carbohydrate concentrate (*i.e.* as a food capable of replacing concentrates in the productive part of the ration) is one which appears to have escaped recognition, presumably on account of the rather high fibre content of this feeding stuff, which has led the stockfeeder to regard it as possessing, at best, but a moderate feeding value.

With the object of securing information concerning the feeding value of sugar beet pulp as produced in this country, the investigation which is reported in the present paper was carried out during the autumn and winter of 1927. Data have been obtained respecting:

(1) The composition and digestibility of wet sugar beet pulp.

(2) The composition of dried sugar beet pulp and the digestibility of this feeding stuff when fed to *ruminants* (*a*) in the dry condition, and (*b*) after preliminary soaking in water.

(3) The composition of molasses-sugar beet pulp.

The supplies of fresh and dried beet pulp for the purposes of the trials were obtained from the Ely Beet Sugar Factory; the molasses-sugar beet pulp was supplied by the beet sugar factory at Peterborough.

The Drying of Wet Sugar Beet Pulp.

The pulp remaining after the extraction of the beet sugar contains from 93–95 per cent. of water. This is reduced by pressing to about 85 per cent. The wet sugar beet pulp so obtained is dried by one of the following methods: (1) The Büttner process; (2) The Imperial process.

In the Büttner process, the drying is conducted in a large cylindrical iron drum provided on its internal surface with a system of plates or vanes. The wet beet pulp enters the drying apparatus from above at one end and is passed along into the drum by means of worm action. The drum revolves two and a half times per minute, so that the pulp is kept in continual movement, dropping from plate to plate as a result of the revolving motion. At the inlet end of the dryer is built a brick kiln in which small coal is burnt at bright red heat. At the exit end, a draught is induced through the kiln and the dryer by means of a fan. The pulp as it enters the dryer is exposed to the full heat of the kiln gases, the temperature of the inlet gases being probably in the region of 800–1000° C. So long as the pulp, however, contains an appreciable amount of water, the temperature of the material does not rise beyond 100° C., and consequently no charring occurs.

The influence of the induced draught is sufficient to keep the pulp moving continuously towards the exit, since as drying proceeds, the density of the pulp is reduced and the lighter particles are carried forward. The temperature of the exit gases varies from 110–120° C., this being sufficiently high to prevent condensation of water vapour removed from the pulp.

The dried pulp obtained by this method usually possesses a light brown, slightly scorched colour, as a result of the influence of the high

temperature in the last stages of drying. A Büttner dryer is able to turn out about 36 tons of dried beet pulp every 24 hours.

In the Imperial process, the furnace gases from the boilers are utilised for the purpose of drying the wet beet pulp. These gases have cooled off slightly during transit from the boiler house, the inlet temperature being about 350° C. The drying apparatus consists of an inner revolving drum contained within an outer stationary drum. The furnace gases are led into the inner drum and from thence pass through perforations into the space between the two drums. Here the hot gases encounter the wet pulp, which is kept in continuous agitation by means of plates or vanes fixed to the outer surface of the inner revolving drum. The temperature of the exit gases varies from 95–110° C.

Owing to the lower temperature to which the pulp is exposed in the Imperial drying process, the final product retains its light grey colour and meets with a special demand, especially from Holland. It commands a slightly higher price than the Büttner-dried pulp. For home consumption it is customary to mix the products from the two processes, and it was on such mixed pulp that the dried beet pulp digestion trials in the present investigation were carried out. The Imperial process is not quite so efficient as the Büttner, the rate of drying being about one and a half times as rapid in the latter process.

In the manufacture of molasses-sugar beet pulp, the wet pulp, after leaving the pressers, enters a scroll, at one end of which a stream of molasses is allowed to run on to the pulp. The scroll conveys the material a considerable distance, and in this process, the pulp and molasses become intimately mixed. The mixture then enters the dryer and is dried in the usual way. As made in the Peterborough Beet Sugar Factory, such molasses-beet pulp is said to contain ordinarily about 20 per cent. of sugar.

General Arrangement of Investigation.

The whole trial was divided into four periods. The first period was devoted to the measurement of the digestibility of the sainfoin-rye grass hay which was to be fed along with the sugar beet pulp in the experimental rations. A weight of hay more than ample for the whole experiment was first passed through a chaffing machine. The chaffed material was then thoroughly mixed and sampled by the method of quartering. This sample was reserved for analytical purposes. At the same time, a second sample was taken for the determination of the moisture content, and the rations for the whole preliminary period were weighed out. The

daily ration in this period consisted of 1200 gm. of sainfoin-rye grass hay (moisture content = 13·80 per cent.).

Table I. *Mean composition of sainfoin-rye grass hay (on basis of dry matter).*

	%
Crude protein	11·78
Ether extract	2·74
N-free extractives	44·62
Crude fibre	32·54
Ash	8·32
True protein	9·92
"Amides"	1·86
Lime (CaO)	1·63
Phosphate (P_2O_5)	0·53
Silica	2·38

Although the figures in Table I show that the sainfoin-rye grass hay was rather fibrous in character, yet it was consumed very readily by the experimental animals, and no food residues were left.

The digestibility of dried sugar beet pulp, when fed in the dry condition, was determined in the second feeding period. This was succeeded by a further period in which the dried beet pulp was replaced by fresh wet sugar beet pulp. In the final period, the effect of preliminary soaking in water on the dried sugar beet pulp was investigated. The rations which were fed to the sheep in these periods are shown in Table II.

Table II. *Experimental rations fed to the sheep in the digestion trials.*

Period	Ration
2	400 gm. chaffed sainfoin-rye grass hay (dry matter content =86·68 %) 800 gm. dried sugar beet pulp (fed dry; dry matter content =86·13 %)
3	400 gm. chaffed sainfoin-rye grass hay (dry matter content =87·62 %) 4600 gm. wet sugar beet pulp (mean dry matter content =15·03 %)
4	400 gm. chaffed sainfoin-rye grass hay (dry matter content =89·08 %) 800 gm. dried sugar beet pulp (fed after soaking; dry matter content =88·43 %)

During the carrying out of the digestion experiment on the wet sugar beet pulp, absolutely fresh consignments of this material were transported daily from the Ely Beet Sugar Factory. The material was spread out in a thin layer on a cold stone floor to prevent "heating" and was weighed out on the following morning for feeding to the sheep, a sample being taken at the same time for moisture determinations. The risk of "heating" during storage of the fresh pulp over short periods, however, was shown in subsequent experiments to be very slight. In one of these experiments, a common sanitary bin was filled with fresh pulp, and a thermometer, contained within a glass tube, was inserted so that its

bulb occupied a central position in the mass of beet pulp. The latter, as it was received from the factory, was slightly warm, having a temperature of 23° C. During the next three days the temperature fell to 11° C. (external temperature = 8–9° C.). Thereafter, the temperature rose to 12·5° C. during the next 48 hours. At the end of this time the beet pulp had acquired a slight, though not unpleasant smell, but had not developed any pronounced acidity.

In period 4 the ration of 800 gm. dried sugar beet pulp was allowed to soak overnight in 2000 c.c. distilled water prior to feeding, this amount of water being easily taken up by the dry feeding stuff.

As the details of procedure in digestion trials have been described very fully in earlier papers (3), it will be unnecessary to recapitulate them at this point. It is only necessary to mention that two pure-bred Suffolk wethers, aged about 19 months at the beginning of the trials, were employed for the purpose of the digestion experiments. They remained in excellent condition throughout the course of the investigation and consumed the rations eagerly, no food residues of any kind being left in any of the experimental periods. During the periods in which beet pulp was fed, the animals were given access to rock salt. Distilled water was given *ad lib.*

The experimental periods, during which collection and analysis of excreta were made, were of 14 days' duration. At the conclusion of such a period of controlled feeding the animals were removed from the metabolism crates and given the run of outdoor pens. In order to ensure that the well-being of the sheep was not being prejudiced by a continuous diet consisting largely of sugar beet pulp, a ration which included fresh green food and a little linseed cake was fed to the animals for a few days after their removal from the crates. They were then gradually brought on to the next experimental ration and, after having subsisted on this for a preliminary period of seven days, were placed in the metabolism crate again for the digestion measurements.

COMPOSITION OF SUGAR BEET PULP.

The results obtained in the analysis of the representative samples of dried sugar beet pulp, wet sugar beet pulp and molasses-sugar beet pulp are recorded in Table III.

Comments on Table III.

A number of determinations were carried out on different days of the moisture content of wet sugar beet pulp as it leaves the pressers. The

values for the percentage of dry matter ranged from 13·90 to 16·74 per cent., the mean value of all the determinations being 14·70 per cent. It may be inferred therefore that, on an average, wet sugar beet pulp will contain round about 15 per cent. of dry matter.

Table III. *Composition of the samples of sugar beet pulp (on basis of dry matter).*

	Dried sugar beet pulp (%)	Wet sugar beet pulp (%)	Molasses-sugar beet pulp (%)
Crude protein	9·88	10·56	11·98
Ether extract	0·71	0·47	0·41
N-free extractives	65·69	63·83	64·72
Crude fibre	20·28	20·61	16·80
Ash	3·44	4·53	6·09
True protein	9·60	10·15	8·20
"Amides"	0·28	0·41	3·78
Lime (CaO)	1·36	1·67	1·35
Phosphate (P_2O_5)	0·20	0·23	0·19
Silica (SiO_2)	0·34	1·40	1·45
Potash (K_2O)	0·66	Not determined	1·49
Soda (Na_2O)	0·27	,,	0·34

A knowledge of the moisture content of dried sugar beet pulp is of obvious importance when purchasing this feeding stuff, since the percentage of moisture may vary within the wide limits of 5 and 16 per cent. The sample used in the present feeding trials contained 13·87 per cent. of moisture. A well-dried and well-stored sample, however, should contain no more than about 10 per cent. It is strongly to be recommended (although the writers are well aware of the difficulty of putting the recommendation into practice) that the drying process should be so regulated that the moisture content of the pulp *at the time of weighing into the sacks* should always be in the neighbourhood of 10 per cent. A 1-cwt. sack of dried beet pulp would then always contain approximately the same weight of *dry* matter, and this would obviously be unaffected by moisture taken up during storage or transport. A similar recommendation has recently been urged in connection with the drying of cooked flaked maize (4).

Sugar beet pulp contains in its dry matter no more protein than does an average sample of meadow hay. It is also deficient in mineral substances. Obviously, therefore, beet pulp can only give satisfactory results in the feeding of stock when due attention is paid to the necessity for including in the ration other feeding stuffs which are rich in protein and ash. Almost the whole of the nitrogen of sugar beet pulp is present in the form of true protein, the soluble "amide" substances originally present in the beet having been removed almost entirely during the process of extraction of the sugar.

As a source of oil, sugar beet pulp is of negligible importance. Its content of crude fibre, on the other hand, is very high, and in this respect it is sharply distinguished from mangolds, which, on the basis of dry matter, contain less than 8 per cent. of crude fibre. The value of beet pulp as a feeding stuff will therefore depend in large measure on the ability of ruminant animals to digest and utilise the fibre constituent. This, in turn, will be determined by the degree of lignification of such fibre, a question which will be dealt with fully later in this paper.

Sugar beet pulp is essentially to be regarded as a source of carbohydrate, the dried pulp, on the basis of a 10 per cent. moisture content, containing as much as 59 per cent. of N-free extractives. It is of interest to inquire into the chemical nature of the carbohydrate which remains in the pulp after removal of the sugar. Sugar beet pulp always contains small quantities of sugar which fails to be extracted during the diffusion process. The amount so remaining will obviously depend on the efficiency with which the extraction is carried out. It varies from 1 to 6 per cent. in the dried beet pulp. Determinations carried out on the sample used in the present feeding trials showed that it contained 2·6 per cent. of sugar.

The carbohydrate of sugar beet pulp, however, consists mainly of pectic substances. As the chemistry of these polysaccharides is still incompletely understood, the writers will not attempt at this point to give more than a brief summary of their properties and chemical nature, though some knowledge of these peculiar substances is naturally essential if the feeding properties of sugar beet pulp are to be appreciated intelligently.

In its insoluble form, pectin constitutes, in loose chemical association with cellulose, the middle lamella of the cell walls of many plant tissues, such as those of fleshy roots, stems and fruits like turnips, beet-root, rhubarb stems, apples, cherries, etc. To this insoluble form the name of pectose has been given. Under the influence of a plant enzyme known as pectosinase, the insoluble form is converted into a soluble form known as pectin. This change occurs during the ripening of succulent fruits, a change which is accompanied by tissue disintegration. It can also be brought about by hot acid hydrolysis of pectose (*e.g.* with 0·5 per cent. oxalic acid, tartaric acid or citric acid, or with $n/20$ hydrochloric acid). Pectin is precipitated from its aqueous extracts by means of alcohol as a voluminous gel.

By the action of a second enzyme pectase, which is abundant in lucerne, clover and carrots, pectin is transformed into methyl alcohol

and a gel of pectic acid. Pectin is regarded as methoxylated pectic acid. The alkaline hydrolysis of pectin, using $n/10$ sodium hydroxide, also changes it into methyl alcohol and sodium pectate, the latter giving a gel of calcium pectate by addition of calcium chloride solution.

The action of a third enzyme pectinase (present in germinating barley) causes the breakdown of pectin with the appearance of considerable amounts of reducing sugars. Ehrlich (5), from his studies of the breakdown products of pectin during acid hydrolysis, concluded that pectin is a calcium-magnesium salt of anhydro arabino-galactose—methoxy-tetra-galacturonic acid, the arabinose being loosely combined and sometimes replaced by methyl pentose. Fellenberg (6), however, regards the calcium and magnesium as associated impurities and concludes that pectin arises from the coupling of two molecules of arabinose, one of methyl pentose, one of galactose and eight of galacturonic acid in the form of its methyl ester, the combination of these twelve molecules being accompanied by the elimination of twelve molecules of water.

Pectin has considerable technical significance in the making of jam, its presence in fruits being responsible for the setting of the final product. It also has the peculiar property of being able, when present in but small amount (0·2 to 1 per cent.) and within a suitable range of P_H, to impart a gelatinous condition to sugar and water, and for that reason is extensively employed in the manufacture of fruit jellies.

Schryver and Haines (7) have demonstrated that a hot solution of ammonium oxalate (0·5 per cent. strength) is an effective solvent for all pectic substances. Preliminary experiments, conducted in collaboration with Mr A. J. Codling, have shown that about 40 gm. of crude pectin (as precipitated by alcohol from the extracts) can be extracted, by exhaustive treatment with 0·5 per cent. ammonium oxalate at 98–100° C., from 100 gm. of sugar beet pulp containing about 57 gm. of N-free extractives. Of obvious importance, therefore, are the questions relating to (1) the digestive mechanism whereby the animal is able to utilise pectose, (2) the degree to which pectose can be digested and utilised by the farm animal, and (3) the nature of the products which become available for absorption into the organism during the digestion of pectose.

From the standpoint of mineral composition (see Table III) sugar beet pulp must be regarded as deficient, containing only 3–5 per cent. of ash on the basis of dry matter. Lime is the most abundant mineral contained in the ash, potash coming next in amount, whereas phosphate and soda are present in quite small proportions. On the basis of the

figures recorded in Table III, and employing unit prices for April, 1928: N = 9*s*. 11*d*.; P_2O_5 = 3*s*. 10*d*.; K_2O = 3*s*. 3*d*., one ton of dried sugar beet pulp containing 10 per cent. of moisture possesses a manurial value of 9*s*. 0*d*.

The data for the composition of molasses-sugar beet pulp (see Table III) display the characteristics which would be anticipated from a knowledge of the method of manufacture of this feeding stuff. Beet molasses contains on an average about 22 per cent. of moisture, 11 per cent. of crude protein (of which only about 0·5 per cent. consists of true protein), 60 per cent. of carbohydrate (mainly cane sugar with about 3 per cent. of raffinose) and 7 per cent. of ash. The last-named constituent is particularly rich in alkaline salts, especially those of potash, but contains very little lime and no phosphate.

The molasses-sugar beet pulp used in the present experiments was a well-dried sample, containing only 8·2 per cent. of moisture. As would be expected, its composition differed from that of ordinary beet pulp in the following particulars. It was somewhat poorer in true protein, but much richer in respect of "amide" substances; it contained a smaller percentage of fibre, but a higher percentage of ash. The mineral fraction, moreover, was much richer in respect of potash. The manurial value per ton of such molasses-beet pulp containing 10 per cent. of moisture works out at 12*s*. 4*d*.

RESULTS OF DIGESTION TRIALS.

The mean results for the digestion coefficients obtained in the several periods of experiment are shown in Table IV. The experimental data necessary for the calculation of these digestion coefficients are recorded in the appendix to this paper.

Table IV. *Summary of digestion coefficients (mean for two sheep).*

Period ...	1. Sainfoin-rye grass hay %	2. Dried sugar beet pulp fed dry %	4. Dried sugar beet pulp fed after soaking %	3. Wet sugar beet pulp %
Dry matter	57·0	84·0	84·2	83·2
Organic matter	58·7	86·5	86·5	86·5
Crude protein	56·4	59·4	58·3	61·1
Ether extract	40·7	—	—	—
N-free extractives	64·1	92·0	91·1	91·0
Crude fibre	53·5	87·7	89·7	89·8

Comments on Table IV.

A striking feature of the data recorded in Table IV is the close agreement which is manifested between the mean values for the digestion

coefficients obtained in the different sugar beet pulp periods. In the case of the digestion coefficient of the organic matter of the beet pulp, for instance, the same mean value, namely 86·5 per cent., was obtained in all three periods. Such very close agreement, however, must be regarded as somewhat fortuitous, since an examination of the appendix, in which the data for the individual sheep are recorded, reveals the fact that the results for the separate sheep in any particular period displayed bigger differences than any which occurred between the mean results of the three beet pulp periods. This was especially the case with the digestion coefficients of the crude protein constituent.

The behaviour of the sheep during the whole course of the digestion trials was satisfactory in every way. They consumed the different rations very readily and no food residues were left in any of the periods. Evidences of the slight laxative effect of sugar beet pulp were obtained here and there, though this effect was never very serious, leading merely to a slight temporary softening of the faeces. The laxative action, slight though it was, appeared to be sufficient to cause a slight depression of the digestibility of the beet pulp. For instance, in both period 3 (wet sugar beet pulp) and period 4 (dried beet pulp fed after soaking) the faeces of Sheep II were quite normal, whereas those of Sheep I were of a moister and softer consistency. In both these periods, the digestion coefficients for Sheep I are slightly lower than those for Sheep II, the difference being most marked in the case of the protein constituent. To this effect, therefore, are probably to be attributed any differences in the extent to which the sheep were able to digest the nutrients of the sugar beet pulp.

The data in Table IV reveal clearly the highly digestible character of sugar beet pulp when consumed by ruminants, as much as 86·5 per cent. of the organic matter of the food being digested and utilised by the animal. On account of its high fibre content, sugar beet pulp has hitherto been generally regarded as being more nearly related in character to the coarse fodders than to the concentrates. This view, however, must obviously be discarded, and sugar beet pulp must henceforward be included in the class of concentrated feeding stuffs, a conclusion which is further emphasised by the comparative data given in Table V.

Table V. *Digestion coefficients of the organic matter of sugar beet pulp and typical concentrates.*

Sugar beet pulp (%)	Barley(8) meal (%)	Maize(9) meal (%)	Flaked(9) maize (%)	Linseed(10) cake (%)	Palm kernel(11) cake (%)
86·5	81·7	87·8	95·4	80·1	70·8

It will be noted from Table V that sugar beet pulp is more digestible than palm kernel cake, linseed cake and barley meal. Its digestibility compares very satisfactorily with that of another important carbohydrate food, namely, maize meal. It is also interesting to realise (see Table IV) that the process of drying the wet sugar beet pulp in the factory does not depress its digestibility. Further, from the standpoint of digestibility, it is immaterial whether the dried product is included in the rations of ruminants in the dry or the soaked condition, preliminary soaking of the dried beet pulp in water prior to feeding having occasioned no measurable improvement in the degree to which the material was digested by the sheep.

It is of special importance to note the extent to which the N-free extractives and crude fibre of the beet pulp were digested by the sheep, since these constituents comprise respectively about 65 and 20 per cent. of the dry matter of the feeding stuff. The digestion coefficients of the N-free extractives were high throughout, being 92·0, 91·1 and 91·0 per cent. respectively in periods 2, 4 and 3. Factory drying, therefore, does not affect the digestibility of this constituent, nor is anything to be gained in this respect by soaking the dried beet pulp before feeding. The significance of these high values is made clear by the data recorded in Table VI.

Table VI. *Digestion coefficients of the N-free extractives of sugar beet pulp and of typical concentrates.*

Sugar beet pulp (%)	Barley (8) meal (%)	Maize (9) meal (%)	Flaked (9) maize (%)	Linseed (10) cake (%)	Palm kernel (11) cake (%)
91·0–92·0	88·7	92·0	97·1	80·5	78·6

It may be concluded from Table VI that ruminants are able to digest the N-free extractives of sugar beet pulp more efficiently than those of protein concentrates like palm kernel cake and linseed cake. From the point of view of digestibility of this constituent, sugar beet pulp and maize meal may be regarded as almost equal.

The digestion coefficients for the crude fibre of the sugar beet pulp (namely 87·7, 89·7 and 89·8 per cent. for periods 2, 4 and 3 respectively) are the highest which have so far been obtained in digestion trials at Cambridge for fibre digestibility, being even higher than the best value obtained for the digestibility of the fibrous constituent of young pasture grass, namely, 85·8 per cent. (12). The fibre in sugar beet pulp is very little inferior in respect of digestibility to the N-free extractives, and it is therefore legitimate to conclude that this constituent is present almost

wholly in the form of simple cellulose, unmixed with any significant amount of the indigestible lignocellulose.

The questions next arise as to (1) the mechanism whereby the N-free extractives and crude fibre, which together form about 85 per cent. of the dry matter of sugar beet pulp, are digested in the ruminant tract, and (2) the nature and nutritive value of the products which arise in the course of their digestion. It has already been shown that the N-free extractives of sugar beet pulp contain only a very small proportion of cane sugar, amounting in the present instance to 2·6 per cent. of the dry matter of the beet pulp. The main carbohydrate present is the polysaccharide pectose. Although the existence of at least three enzymes, pectosinase, pectase and pectinase, capable of acting on pectic substances, has been definitely proved in plant tissues, it is doubtful whether the secretions of the digestive tract of animals contain any enzyme capable of causing the breakdown of the pectose complex. This latter possibility, however, is being investigated in this Institute at the present time. In the absence of an enzyme mechanism for the purpose, it must be assumed that the pectose in the beet pulp is rendered available for absorption into the blood stream by the digestive action of bacteria.

The existence of bacteria and fungi which have the power of breaking down pectose has long been recognised. In the process of flax retting, the pectic cell cement is decomposed by a specific organism, *Granulobacter pectinovorum*, which is now regarded as a variety of *B. amylobacter*. The cellulose constituent is unaffected during the process of pectic fermentation. Flax retting may also be brought about artificially by the common hay and potato organisms, *B. subtilis* and *B. mesentericus*, the insoluble pectose in the tissues being first hydrolysed to pectin and finally to sugars like galactose and arabinose. Under certain conditions, the action may proceed a stage further, giving rise to carbon dioxide, methane, acetic acid, butyric acid and traces of lactic acid. It is considered probable that the hydrolysis of pectose by bacteria is effected by secretions containing all the enzymes capable of bringing about modification of the pectic compounds.

It is proposed to submit to further investigation, from both the qualitative and quantitative standpoints, the question of the breakdown of pectose by bacteria, especially by the micro-organisms which inhabit the rumen of animals. It will be necessary to assume for the present, however, that the rumen is the seat of such bacterial activity, and that by this means the pectose is broken down mainly to products like galactose, arabinose and galacturonic acid, together with, as in the case

of bacterial digestion of cellulose, minor quantities of methane, carbon dioxide, acetic acid and butyric acid. As with many other feeding stuffs (for example, green fodders and oil cakes), in which the true chemical nature of the N-free extractives is obscure, it is fair to assume that the digestible portion of the N-free extractives of sugar beet pulp has a value to the animal equal to that of the same weight of starch, an assumption which is in keeping with the results of Kellner's respiration chamber studies of this feeding stuff (13) and, further, with the satisfactory results obtained with sugar beet pulp in practical feeding tests carried out in America, Germany, Sweden and elsewhere.

During the carrying out of the present digestion trials, daily tests were made for reducing sugar in the urine of the sheep, since the presence of appreciable amounts of pentose sugar in the diet of an animal may lead to the elimination of such material in the urine. The sugar tests, however, invariably yielded negative results, and it may therefore be concluded that no pentose sugar was being lost in this manner when the animals were subsisting on a ration containing a large proportion of sugar beet pulp, a feeding stuff which must, among other compounds, give rise to arabinose during digestion.

The mechanism whereby the fibre in the sugar beet pulp is rendered available for the nutrition of the animal has been explained in a recent communication (14). The cellulose component is transformed mainly into glucose by the controlled activity of cellulose-hydrolysing bacteria in the rumen. The striking fact is brought to light, therefore, that more than four-fifths of the dry matter of this feeding stuff is digested not by enzymic processes, but by the agency of bacteria. In view of this circumstance, it is of importance to emphasise the statement that the results of the present trials in respect of the digestibility and nutritive value of sugar beet pulp *are only applicable to ruminant animals.* The extent to which *swine* are able to digest and utilise beet pulp will form the subject of a further investigation to be carried out in the coming autumn.

The data for the digestion coefficients of the protein constituent of the sugar beet pulp (see Table IV) present several features of interest. It will be noted in the first place that the factory process of drying the wet beet pulp does not lead to a diminution of protein digestibility, the mean digestion coefficients in the three periods of pulp feeding being 59·4, 58·3 and 61·1 per cent. respectively. These figures may be taken as indicating equal digestion of the protein whether the beet pulp be fed in the fresh or the dried condition, and when the dried pulp is soaked in

water prior to feeding. Much bigger differences than these were noted between the results for the individual sheep in the separate periods, probably as a consequence of the slight laxative action of the beet pulp in the case of one of the experimental animals.

The low values of the protein digestion coefficients of the beet pulp, in comparison with those of the fibre and N-free extractives, are particularly noteworthy. Indeed, the protein of the sugar beet pulp is only slightly better digested than the corresponding constituent of the sainfoin-rye grass hay. In early German investigations into the feeding value of sugar beet pulp (15), it was recognised that this feeding stuff appears to exert a depressing effect on the digestibility of the protein constituent of the ration. That the protein digestion coefficients obtained in the animal trials do not represent the real extent to which beet pulp protein can be broken down by enzymes is apparent from measurements which were made of the solubility of this constituent in pepsin-HCl (Stutzer's method of artificial digestion). By this means, the much higher value of 75·3 per cent. was obtained for the digestion coefficient of the crude protein of the dried beet pulp.

Two explanations may be put forward to account for the low protein digestion coefficients obtained by animal experiment. (1) The inclusion of sugar beet pulp in the ration may lead to a big increase in the output of metabolic nitrogenous material in the faeces. (2) The beet pulp may exert a direct depressing influence in the following way. In the light of what has been written concerning the digestion of sugar beet pulp in the ruminant tract, it may be inferred that this process is only brought about as a result of unusually intense bacterial activity in the rumen of animals. It is probable, therefore, that considerable amounts of the nitrogen in the ration are utilised for the purposes of bacterial development and are thereby transformed into less easily digested nitrogenous material. By such action, the digestibility of the protein of both hay and beet pulp would be depressed.

That some such explanation is not unlikely is evident from results which were obtained in a recent investigation into the changes which occur during the making of stack silage (16). During storage of the crop in the stack, the digestion coefficient of the protein of the green crop fell from 64·5 per cent. to the abnormally low level of 12·2 per cent. This depression was shown to be due to a portion of the protein of the green crop having undergone transformation into a dark brown nitrogenous product, which was not only insoluble in hot dilute acid and alkali, but also remained undissolved after prolonged treatment with pepsin-HCl

at 37° C. This profound change in the chemical character of the nitrogenous components of the crop was brought about by bacterial agency, in particular by the activity of cellulose-splitting micro-organisms, which were so much in evidence at one stage of storage as to occasion a marked peak in the temperature curve of the stack.

It was not found possible, by means of animal experiment, to secure figures representing the extent to which the ether-soluble constituents of the sugar beet pulp were digested (see Table IV). This was scarcely surprising, however, since the dried beet pulp contained only 0·71 per cent. of crude oil in its dry matter, and the amount included in the daily allowance of 800 gm. of dried beet pulp was less than 5 gm. The difficulty of measuring the extent to which such a small amount of ether extract is digested becomes further enhanced by the fact that the solid excreta of animals contain not only the ether-soluble constituents appertaining to the undigested food residues, but also similar substances of metabolic origin. It may, however, be concluded that sugar beet pulp, as a source of digestible oil, is of quite negligible importance.

Before leaving this phase of the subject, it will be of interest to compare the results of the present trials with those obtained in earlier German and American investigations into the digestibility of sugar beet pulp. The comparison is shown in Table VII.

Table VII. *Comparison of digestion coefficients of sugar beet pulp obtained in present trials with those obtained in German and American trials.*

Authority*	Dry matter %	Organic matter %	Crude protein %	Ether extract %	N-free extractives %	Crude fibre %
Present trials (mean results)	83·8	86·5	59·6	—	91·4	89·1
Mentzel and Lengerke (1898) (*a*)	82	—	63	—	84	83
American State Expt. Stations (mean of 3 trials) (*b*)	75	—	52	—	83	83
Kellner (extreme values in 11 trials) (*c*)	—	74–80	34–63	—	82–91	67–84
Lehmann (experiments with pigs) (*d*)	—	81	32	—	91	86

* Index to references in Table VII:

(*a*) Henry, *Feeds and Feeding*, 4th edn, 1902.

(*b*) Henry and Morrison, *Feeds and Feeding*, 17th edn, 1917.

(*c*) Kellner, *Ern. d. landw. Nutzt.*, 1905 edn.

(*d*) Lehmann, *Landw. Jahrb.* 1902, Ergänzungsb. II.

Comments on Table VII.

It will readily be seen that the results of the present investigation into the digestibility of sugar beet pulp as made at the present time in this country compare very favourably with the results of earlier German and American digestion trials. All the trials are in agreement in assigning a comparatively low digestibility to the protein constituent of the beet pulp. None of the experimenters was able to evaluate the digestibility of the ether extract. Further, the high values obtained in the present trials for the digestion coefficient of the fibrous constituent are substantially confirmed by the results of the older trials.

The most interesting figures, however, in Table VII are those given by Lehmann showing the extent to which sugar beet pulp is digested by swine. As long ago as 1902 this investigator made measurements of the digestibility of a large number of common feeding stuffs, using pigs as his experimental animals. Although comparatively poor results were obtained with a number of foods (*e.g.* palm kernel cake and rice meal) yet surprisingly good results were obtained with roots. It will be noted, for instance, that the digestion coefficients obtained for the N-free extractives and the crude fibre of dried beet pulp were of the same order of magnitude as those obtained with sheep in the present trials. This somewhat unexpected result encourages the belief that sugar beet pulp may be an extremely useful food for swine. In view, however, of the limited experience of stockfeeders in this country in regard to the use of sugar beet pulp for pig-feeding, it is proposed to carry out work in this connection during the coming autumn and, in particular, to repeat Lehmann's work on the digestibility of this feeding stuff when consumed by pigs.

Table VIII. *Digestible nutrients in sugar beet pulp (present trial) and in maize meal (on basis of dry matter).*

	Sugar beet pulp* %		Maize meal(13) %	
Digestible crude protein	5·89		8·16	
Digestible ether extract	—		4·48	
Digestible N-free extractives	60·04	78·11	75·52	77·02
Digestible crude fibre	18·07		1·50	
Total digestible organic matter	84·00		89·66	

* Employing mean digestion coefficients of periods 2, 3 and 4 (see Table VII) and data for composition of dried sugar beet pulp (see Table III).

Comments on Table VIII.

The data compiled in Tables V and VI have revealed an interesting parallelism between maize and dried sugar beet pulp in respect of the digestion coefficients of the N-free extractives and total organic matter of these carbohydrate-rich foods. This parallelism receives further emphasis from the results shown in Table VIII, from which it appears justifiable to conclude that *dried sugar beet pulp must be included with feeding stuffs like maize meal in the class known as carbohydrate concentrates*. 100 parts of the dry matter of maize contain 89·6 parts of digestible organic matter, including 77 parts of digestible carbohydrate (*i.e.* digestible N-free extractives plus digestible fibre); the corresponding values for sugar beet pulp are 84 and 78. With both feeding stuffs, a very large proportion of the digestible organic matter consists of digestible carbohydrate; it would thus be necessary in practice to supplement both sugar beet pulp and maize with feeding stuffs which are richer in protein. Further, both these carbohydrate foods have the characteristic of being deficient in respect of mineral constituents.

In calculating the starch equivalent of sugar beet pulp from its digestible composition, it is in the first place necessary to decide the value of its availability factor (V). This question was investigated many years ago by Kellner (13) for both wet and dried sugar beet pulp, and the results of his experiments are shown in Table IX.

Table IX. *Determination of the percentage availability of sugar beet pulp* (Kellner).

	Dry pulp	Wet pulp
Per 100 gm. dry matter consumed:		
Storage calculated on basis of digestible nutrients	172·6 Cal.	176·4 Cal.
Actually found in animal experiment	135·3 „	166·0 „
Difference	−37·3 „	−10·4 „
Reduction as % of calculated value	21·6 %	5·9 %

On the basis of the results in Table IX, Kellner concluded that the digestible nutrients of the wet beet pulp possessed a higher value to the animal than those of the dried pulp. He assigned the values 94 and 78 per cent. to the availability factors of the wet and dried beet pulp respectively. This difference in the productive values of the two kinds of pulp was attributed to the greater difficulty experienced by the animal in masticating the dried product. For that reason it is of obvious importance, when large allowances of dried beet pulp are included in the rations of farm animals, that the feeding stuff should be well soaked and softened in water prior to feeding, in order that the maximum amount

of starch equivalent shall be available for productive purposes in the body of the animal.

The question as to the value of V in the case of dried sugar beet pulp which has been softened in water before feeding has been settled by Nils Hansson. For many years the Swedish experimenter has been carrying out investigations into the feeding value of the dry matter of different root crops and of sugar beet pulp, and, as a result of numerous tests with animals, has come to the conclusion that the availability factor for dried sugar beet pulp soaked in water before feeding is best expressed by the figure 87 per cent. (17). Moreover, if the dried beet pulp, fed in the dry condition, is well mixed with the other concentrates of the ration so as to ensure its softening by salivation, then the same availability factor, namely, 87 per cent., may be employed[1].

The availability factors given in Table X may therefore be regarded as authoritative.

Table X. *Percentage availability of digestible nutrients in sugar beet pulp.*

	V (%)
Wet sugar beet pulp	94
Dried sugar beet pulp, soaked in water before feeding	87
Moderate allowances of dried sugar beet pulp, fed dry, in intimate admixture with other concentrates	87

To the statement in Table X it is merely necessary to add that where liberal allowances of dried sugar beet pulp are included in the ration, it will always be advisable to soak the food in water before feeding. This procedure will not only ensure a higher availability of the digestible nutrients for productive purposes in the animal, but will also obviate the risk of choking trouble which sometimes arises during consumption of the dried product. This trouble is apt to be encountered with sheep, the latter, on account of their liking for dried beet pulp, being liable to devour it too greedily.

Table XI. *Starch equivalents and nutritive ratios of sugar beet pulp, maize meal and barley meal.*

	Sugar beet pulp			
	Wet beet pulp (85 % moisture $V=94$)	Dried beet pulp (10 % moisture $V=87$)	Barley meal (10) (14·9 % moisture $V=98$)	Maize meal (10) (13 % moisture $V=100$)
S.E. per 100 lb.	11·8 lb.	65·5 lb.	71·0 lb.	81·4 lb.
S.E. per 100 lb. of dry matter of food	78·6 lb.	72·8 lb.	83·4 lb.	93·6 lb.
Nutritive ratio	13·3	13·3	10	11

[1] Personal communication from Prof. Hansson.

Comments on Table XI.

Further confirmation of the concentrate character of dried sugar beet pulp is forthcoming from the data set out in Table XI, where it is shown that 100 lb. of the dry matter of this feeding stuff is equal, for purposes of fattening, to 72·8 lb. of starch. It will be noted that although sugar beet pulp and maize are very similar in respect of content of digestible organic matter, yet the starch equivalent of the latter is appreciably higher than that of the former feeding stuff. This is mainly due to the higher availability of the digestible nutrients in maize, V for this feeding stuff having the full value of 100 per cent.

It may be concluded from the data in Table XI that, for purposes of fattening in the *ruminant* animal, 1 lb. of dried sugar beet pulp (moisture content = 10 per cent.) may replace 0·8 lb. of maize (moisture content = 13 per cent.). According to the Scandinavian system of food values (17) 1 food unit is contained in 1·2 kg. of dried sugar beet pulp and in 0·95 kg. of maize. From these data it will be seen that 1 kg. of dried beet pulp is regarded as being interchangeable with 0·8 kg. of maize, a figure which affords a striking confirmation of the result arrived at in the present investigation, especially as the Scandinavian result represents the conclusion drawn from a line of enquiry essentially different from that followed in the present work, namely, large-scale practical feeding tests on the farm instead of digestion trials prosecuted under laboratory conditions.

In this country it has become customary to regard sugar beet pulp solely as a substitute for roots in the ration and to advise against using it for the replacement of concentrates. This view, however, is seen, in the light of the present work, to be too narrow. Dried sugar beet pulp must be regarded as a carbohydrate concentrate, 1 lb. of which is capable of replacing 0·8 lb. of maize or 0·9 lb. of barley in the productive part of the rations of ruminant animals.

Table XII. *Relative food values of dried sugar beet pulp, maize meal and barley meal.*

	Dried sugar beet pulp	Maize meal*	Barley meal*
	£ *s.* *d.*	£ *s.* *d.*	£ *s.* *d.*
Price per ton	5 10 0	10 12 0	12 5 0
Manurial value per ton	9 0	11 0	10 0
Food value per ton	5 1 0	10 1 0	11 15 0
Price per unit of starch equivalent	1 6	2 6	3 4
Price per lb. of starch equivalent	0·8*d.*	1·34*d.*	1·78*d.*

* Quoted from *J. Min. Agric.* April 1928.

That dried sugar beet pulp, moreover, constitutes a relatively cheap source of digestible carbohydrate is apparent from the data compiled in Table XII, where the prices per unit and per lb. of starch equivalent in dried beet pulp, maize meal and barley meal are given.

In a recent communication (18) Prof. T. B. Wood has demonstrated very clearly that an all-round standard of high productivity in the various branches of animal husbandry in this country will not be attainable until means have been found for bringing about a material increase in the supply of concentrated foods for feeding to farm animals. Recent work in this Institute (19, 12, 20) has shown that the available supply of protein concentrates may be augmented considerably by adopting a system of close grazing of pastures, since the dry matter of young pasture herbage is a protein-rich food of high digestibility. The results of the present investigation have demonstrated further that in dried sugar beet pulp the farmer possesses what is, for this country, a new and relatively cheap carbohydrate concentrate. By the fuller utilisation of these sources of digestible protein (young pasture herbage) and digestible carbohydrate (sugar beet pulp) the farmer will be able to solve many of the problems associated with intensive production in farm animals.

Summary.

The object of the investigation which has been described in the present communication has been to secure information concerning the feeding value of sugar beet pulp as produced at the present time in this country. Data have been obtained respecting:

(1) The composition and digestibility of wet sugar beet pulp.

(2) The composition of dried sugar beet pulp and the digestibility of this feeding stuff when fed to ruminants (*a*) in the dry condition, and (*b*) after preliminary soaking in water.

(3) The composition of molasses-sugar beet pulp.

Data have been given showing the amounts of sugar beet by-products which are becoming available for use on the farm.

The commercial processes of drying wet sugar beet pulp, and the method of manufacture of molasses-sugar beet pulp, have been described.

It has been shown that crude fibre (20·3 per cent.) and N-free extractives (65·7 per cent.) constitute together more than four-fifths of the dry matter of sugar beet pulp, the latter being deficient in respect of protein, ash and oil. The carbohydrate of sugar beet pulp is invested with special interest, being mainly in the form of pectose. A short account of the chemistry of the pectic substances has been given.

The manurial value per ton of dried sugar beet pulp has been shown to be 9*s.* 0*d.*; that of molasses-sugar beet pulp 12*s.* 4*d.*

Sugar beet pulp has been shown to be highly digestible in the ruminant organism. In respect of the digestibility of its N-free extractives and total organic matter, as well as in respect of its content of digestible organic matter, it compares very satisfactorily with maize meal. The process of drying the wet beet pulp in the factory does not in any way depress its digestibility. Further, from the standpoint of digestibility, it is immaterial whether dried sugar beet pulp is included in the rations of ruminants in the dry or the soaked condition. When, however, liberal allowances of the dried product are being fed to animals, it is desirable that the food should be well softened in water prior to feeding. This procedure will ensure a higher availability of the digestible nutrients for productive purposes in the animal and further will avert risk of choking trouble which sometimes arises, especially with sheep, during consumption of the dried beet pulp.

The fibrous constituent of sugar beet pulp is very little inferior in respect of digestibility to the N-free extractives, a result which justifies the conclusion that the fibre in this feeding stuff is present almost wholly in the form of simple cellulose, unmixed with any significant amount of the indigestible lignocellulose.

The digestion coefficient of the protein constituent is relatively low. It would appear that the inclusion of sugar beet pulp in the ration may have the effect of depressing slightly the extent to which the animal is able to utilise the protein of its food. The possible explanations of this effect have been discussed.

Attention has been drawn to the fact that almost four-fifths of the total dry matter of sugar beet pulp is digested not by enzymic processes, but by the agency of bacteria. It is necessary, therefore, to point out that the results of the present investigation, in respect of the digestibility and nutritive value of sugar beet pulp, are only applicable to ruminant animals. The extent to which swine are able to digest and utilise this feeding stuff will form the subject of a separate enquiry.

In this country it has become customary to regard sugar beet pulp solely as a substitute for roots in the ration, and to advise against using it for the replacement of concentrates. The results of the present work have shown that this view is too narrow. Dried sugar beet pulp must be regarded as a carbohydrate concentrate, 1 lb. of which is capable of replacing 0·8 lb. of maize or 0·9 lb. of barley in the productive part of the rations of ruminants. Moreover, from the standpoint of price per

unit or per lb. of starch equivalent, dried sugar beet pulp has been shown to be a cheap source of digestible carbohydrate in comparison with either maize meal or barley meal.

In conclusion, the writers gladly take this opportunity of expressing their gratitude to Edward R. Blount, Esq., of the Ely Beet Sugar Factory, not only for supplying the wet and dried sugar beet pulp which was used in these experiments, but also for granting facilities for inspecting the factory processes of drying the wet sugar beet pulp. Grateful thanks are also tendered to J. N. Mowbray, Esq., of the Peterborough Beet Sugar Factory, for supplying the sample of molasses-sugar beet pulp, together with details of its manufacture.

REFERENCES.

(1) *Farmer and Stockbreeder*, Aug. 22, 1927.
(2) —— Feb. 13, 1928.
(3) Woodman (1922). *J. Agric. Sci.* **12**, 144.
(4) Woodman and Stewart (1927). *J. Agric. Sci.* **17**, 60.
(5) Ehrlich (1917). *Chem. Zentr.* **41**, 197.
(6) Fellenberg (1918). *Biochem. Z.* **85**, 45.
(7) Schryver and Haines (1916). *Biochem. J.* **10**, 539.
(8) Wood and Woodman (1924). *J. Agric. Sci.* **14**, 498.
(9) Woodman (1925). *J. Agric. Sci.* **15**, 1.
(10) Wood, *Rations for Live Stock*, 1927 ed.
(11) Crowther and Woodman (1917). *J. Agric. Sci.* **8**, 429.
(12) Woodman, Blunt and Stewart (1927). *J. Agric. Sci.* **17**, 209.
(13) Kellner. *Ern. d. landw. Nutzt.* 1905 ed.
(14) Woodman (1927). *J. Agric. Sci.* **17**, 333.
(15) Pfeiffer and Lehmann (1885). *J. f. Landw.*, p. 387.
(16) Woodman and Hanley (1926). *J. Agric. Sci.* **16**, 24.
(17) Hansson. *Fütterung der Haustiere*, 1926 ed.
(18) Wood. "The Farmer's Sheet-Anchor," *The Nineteenth Century and After*, Aug. 1927.
(19) Woodman, Blunt and Stewart (1926). *J. Agric. Sci.* **16**, 205.
(20) Woodman, Norman and Bee (1928). *J. Agric. Sci.* **48**, 266.

Appendix I. *Digestion Tables.*

Period 1. (1200 gm. sainfoin-rye grass hay)

	Sheep I							Sheep II						
	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extrac-tives gm.	Crude fibre gm.	Ash gm.	Dry matter gm.	Organic matter gm.	Crude protein gm.	Ether extract gm.	N-free extrac-tives gm.	Crude fibre gm.	Ash gm.
Consumed:	1034·40	948·34	121·85	28·34	461·55	336·60	86·06	1034·40	948·34	121·85	28·34	461·55	336·60	86·06
Voided	440·40	386·63	51·94	18·54	158·94	157·21	53·77	449·02	397·34	54·31	15·06	172·27	155·70	51·68
Digested	594·00	561·71	69·91	9·80	302·61	179·39	32·29	585·38	551·00	67·54	13·28	289·28	180·90	34·38
Digestion coefficients, %	57·43	59·23	57·37	34·58	65·56	53·30	37·52	56·59	58·12	55·43	46·86	62·67	53·74	39·95
Period 2. (400 gm. sainfoin-rye grass hay + 800 gm. dried sugar beet pulp fed dry)														
Consumed: Hay	346·70	317·85	40·84	9·50	154·69	112·82	28·85	346·70	317·85	40·84	9·50	154·69	112·82	28·85
Pulp	689·00	665·30	68·07	4·89	452·61	139·73	23·70	689·00	665·30	68·07	4·89	452·61	139·73	23·70
Total	1035·70	983·15	108·91	14·39	607·30	252·55	52·55	1035·70	983·15	108·91	14·39	607·30	252·55	52·55
Voided	252·76	216·55	43·31	15·51	89·23	68·50	36·21	265·62	226·24	47·62	13·83	93·98	70·81	39·38
Digested	782·94	766·60	65·60	—	518·07	184·05	16·34	770·08	756·91	61·29	0·56	513·32	181·74	13·17
Digested from hay	199·10	188·27	23·43	3·29	101·42	60·13	10·83	196·20	184·67	22·64	4·45	96·95	60·63	11·53
Digested from pulp	583·84	578·33	42·17	—	416·65	123·92	5·51	573·88	572·24	38·65	—	416·37	121·11	1·64
Digestion coefficients of pulp, %	84·74	86·93	61·95	—	92·05	88·69	23·25	83·30	86·01	56·78	—	92·00	86·68	6·92
Period 3. (400 gm. sainfoin-rye grass hay + 4600 gm. wet sugar beet pulp)														
Consumed: Hay	350·50	321·34	41·29	9·60	156·40	114·05	29·16	350·50	321·34	41·29	9·60	156·40	114·05	29·16
Pulp	691·40	660·08	73·01	3·25	441·32	142·50	31·32	691·40	660·08	73·01	3·25	441·32	142·50	31·32
Total	1041·90	981·42	114·30	12·85	597·72	256·55	60·48	1041·90	981·42	114·30	12·85	597·72	256·55	60·48
Voided	275·27	229·03	47·87	13·86	96·78	70·52	46·24	258·12	215·21	44·88	10·91	94·86	64·56	42·91
Digested	766·63	752·39	66·43	—	500·94	186·03	14·24	783·78	766·21	69·42	1·94	502·86	191·99	17·57
Digested from hay	201·28	190·34	23·69	3·32	102·54	60·79	10·94	198·35	186·70	22·89	4·50	98·02	61·29	11·65
Digested from pulp	565·35	562·05	42·74	—	398·40	125·24	3·30	585·43	579·51	46·53	—	404·84	130·70	5·92
Digestion coefficients of pulp, %	81·77	85·15	58·54	—	90·27	87·89	10·54	84·67	87·79	63·73	—	91·73	91·72	18·90
Period 4. (400 gm. sainfoin-rye grass hay + 800 gm. dried sugar beet pulp, soaked before feeding)														
Consumed: Hay	356·30	326·65	41·97	9·76	158·98	115·94	29·65	356·30	326·65	41·97	9·76	158·98	115·94	29·65
Pulp	707·40	683·06	69·89	5·02	464·69	143·46	24·34	707·40	683·06	69·89	5·02	464·69	143·46	24·34
Total	1063·70	1009·71	111·86	14·78	623·67	259·40	53·99	1063·70	1009·71	111·86	14·78	623·67	259·40	53·99
Voided	272·01	232·57	49·50	12·72	103·35	67·00	39·44	258·60	221·95	45·33	12·44	93·74	70·44	36·65
Digested	791·69	777·14	62·36	2·06	520·32	192·40	14·55	805·10	787·76	66·53	2·34	529·93	188·96	17·34
Digested from hay	204·62	193·49	24·08	3·38	104·23	61·80	11·13	201·62	189·77	23·26	4·57	99·63	62·31	11·85
Digested from pulp	587·07	583·65	38·28	—	416·09	130·60	3·42	603·48	597·99	43·27	—	430·30	126·65	5·49
Digestion coefficients of pulp, %	82·99	85·44	54·77	—	89·54	91·03	14·05	85·31	87·55	61·91	—	92·60	88·28	22·55

NOTE: The care of the experimental animals was in the hands of Messrs V. Thurlbourn and C. Bendall.

Appendix II. *Weights of Sheep.*

		Sheep I		Sheep II	
		st.	lb.	st.	lb.
Period 1	Oct. 13, 1927	9	12	9	9
	Oct. 31, 1927	9	12	9	8
Period 2	Nov. 7, 1927	9	10	9	10
	Nov. 24, 1927	9	10	9	10
Period 3	Dec. 1, 1927	10	2	10	1
	Dec. 19, 1927	10	3	10	2
Period 4	Jan. 2, 1928	10	6	10	4
	Jan. 19, 1928	10	8	10	4

(*Received May* 11*th*, 1928.)

THE VITAMIN A AND B CONTENT OF THE PIGEON PEA (*CAJANUS INDICUS*).

BY CAREY D. MILLER.

(*Department of Household Science, University of Hawaii, Honolulu.*)

(With One Text-figure.)

THE pigeon pea (*Cajanus indicus* or *C. cajan*) grown extensively in India, Africa, and other tropical and semitropical countries has attained considerable prominence as a stock food in Hawaii, where it is being grown as an important field and pasture crop in some sections. Its culture and utilisation in Hawaii have been exhaustively treated in a bulletin of the Hawaii Agricultural Experiment Station written by F. G. Krauss (1).

Dr Krauss now of the University of Hawaii, who has spent some twenty years developing new varieties of the pigeon pea that seem best adapted to Hawaiian conditions, furnished the seed and plant meals used in the experiments here reported. The variety used was the New Era Strain D. The entire green plant was dried and made into a meal called in these experiments "plant meal." The seeds of the same variety were also dried and made into a fine meal here called "seed meal."

The meals used for the feeding experiments were similar in composition to those given in the following table from the Hawaii Agricultural Experiment Station bulletin.

Table I. *Average composition of the pigeon-pea products.*

(Based on all available analyses made in Hawaii to Feb. 19, 1920.)

Character of material analysed	Moisture %	Ash %	Crude protein %	Carbohydrates: Crude fibre %	Carbohydrates: Nitrogen free extract %	Nitrogen %	Fat %
Fresh green forage*	70·00	2·46	7·11	10·72	7·88	1·13	1·65
Whole plant cured as hay and ground into meal	11·19	3·53	14·83	28·87	39·89	2·37	1·72
Seed meal	12·26	3·55	22·34	6·44	53·94	3·57	1·46

* Upper third of plant with seed in pod.

The remarkable success of this plant as a feeding stuff, especially in the finishing of young beeves for market as well as for dairy cows and swine, led to the question of its vitamin content compared with other forage crops.

Experimental procedure.

The mothers of all rats used in the experiments had a diet of the following mixture: 1000 gm. whole wheat, 500 gm. whole milk powder, 20 gm. common salt and 100 gm. soy-bean meal. The soy-bean meal was made by cooking yellow soy beans in a pressure cooker for one hour at 15 to 20 pounds pressure, drying them in the oven, and grinding fine. Several times a week fresh alfalfa was also given the mothers.

All experimental animals were kept in individual round wire cages with a raised bottom of wire screen to reduce faeces consumption to a minimum. The cages were cleaned daily and the animals weighed once a week or oftener.

Vitamin A content of plant and seed meals.

In the first experiments carried out in 1924 and 1925 the pigeon-pea meals were incorporated in the diet. The basal diet of meat residue

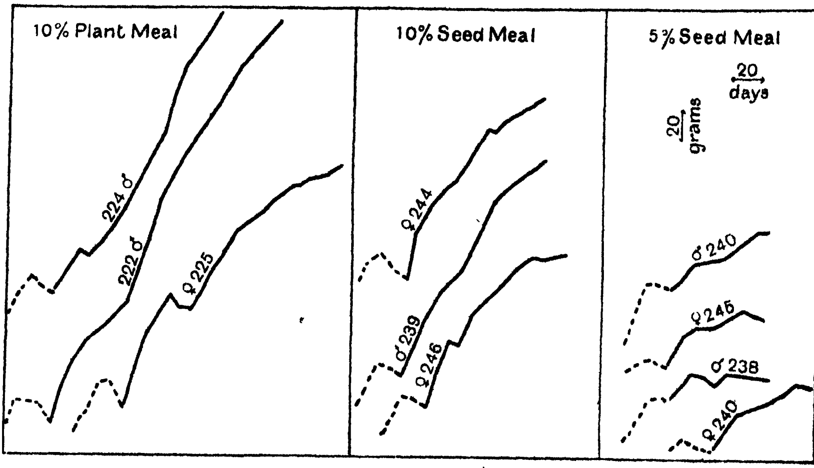


Chart I. Vitamin A of pigeon-pea plant and seed meals.

20 per cent., starch 53 per cent., yeast 3 per cent., salt mixture 4 per cent. and crisco 20 per cent. was fed to the rats until their weights were stationary or declining, when the seed meal and the plant meal were added by replacing 5 per cent. or 10 per cent. of the starch. The results are summarised in Chart I.

In 1926–1927 experiments were undertaken in which Sherman's (2) recommendation for making the results as nearly quantitative as possible was used, that is, in addition to the basal diet small amounts

of weighed material were fed daily in an effort to cause a gain of about 25 gm. in 8 weeks.

The following basal diet was used:

Meat residue[1]	20 %
Starch	60 %
Yeast	5 %
Salt mixture[2]	4 %
Sodium Chloride c.p.	1 %
Crisco	10 %

The prepared meat residue was extracted three times with hot 95 per cent. alcohol following Sherman and Munsell's (3) recommendation for the extraction of casein. Before using, the diet was irradiated in thin layers for two hours in bright sunlight between the hours of 10 a.m. and 3 p.m. to insure its vitamin D content. White albino rats 28 to 29 days old, weighing 45 to 55 gm. were placed on the above diet. When the weights of the animals had become stationary or declining for one week, the weighed amounts of pigeon-pea plant meal and seed meal were fed daily for 8 weeks. The results are summarised in Table II.

Table II. *Results of feeding pigeon-pea plant meal and seed meal for vitamin A content for a period of* 8 *weeks.*

	Number of rats used	Weight of meal fed daily gm.	Average gain in 8 weeks gm.	Remarks
Plant meal	2	0·3	18	No xerophthalmia
	6	0·4	38	No xerophthalmia
Seed meal	4	0·5	4	All had xerophthalmia
	4	1·0	52	3 had severe xerophthalmia, 1 slight

The results indicate that the meal from the entire plant is much higher in vitamin A than the seed meal. As 0·3 gm. of plant meal daily proved insufficient and 0·4 gm. too great an amount to cause the desired gain of 25 gm. in 8 weeks, 0·35 gm. is probably very near the correct amount. None of the animals on plant meal showed signs of xerophthalmia and they were in good condition when killed at the end of 8 weeks.

In the experiments with the seed meal, 0·5 gm. daily proved entirely inadequate to cause the desired gain, while 1·0 gm. proved to be too much. It is suggested that 0·7 or 0·8 gm. daily is near the desired amount. It was remarkable that even the four animals on 1·0 gm. of seed meal daily that made uniformly large gains all developed xeroph-

[1] Prepared according to Osborne, Wakeman and Ferry, *J. Biol. Chem.*, **39**, 37, 1919.

[2] Prepared according to Osborne and Mendel, *J. Biol. Chem.* **37**, 572, 1919.

thalmia. It would appear that the amount of vitamin A (both the growth-promoting and anti-ophthalmic factors) is very much lower in the seed than in the plant. Experiments will be continued to observe the growth using the basal diet unirradiated and irradiated, thus varying the vitamin D and feeding the same daily portion of the seed meal.

In as much as yellow colouring matter and vitamin A have been found to be quite generally associated in plant foods, the development of a seed of the pigeon pea more distinctly yellow in colour might lead to a higher vitamin A content.

Vitamin B content of plant and seed meals.

A few experiments to determine the vitamin B content of the whole plant meal were carried out in 1924–1925. Two rats that were fed 2 gm. of plant meal daily in addition to the basal diet grew better than normal. Two rats fed 1 gm. daily and two fed 0·5 gm. daily did not make normal growth curves.

In 1926–1927, Sherman's (2) recommendation for procedure was followed.

The following basal diet was used:

Meat residue	20 %
Butter fat	63 %
Codliver oil	2 %
Salt mixture	4 %
Sodium chloride c.p.	1 %
Crisco	10 %

The meat residue was the same as that used for vitamin A experiments but was not extracted with alcohol. The salt mixture was identical. The rats used weighed from 48 to 64 gm. at the age of 28 or 29 days when they were put on the above diet and the plant meal and the seed meal in weighed amounts were at once fed daily. The results are summarised in Table III.

Table III. *Results of feeding pigeon-pea plant meal and seed meal for vitamin B content for a period of* 8 *weeks.*

	Number of rats used	Weight of meal fed daily gm.	Average gain in 8 weeks gm.	Remarks
Plant meal	2	0·1	−20	Killed at end of 6 weeks
	2	0·2	− 9	Killed at end of 6 weeks
	2	0·3	2	
	3	0·4	21	
Seed meal	2	0·1	−12	Killed at end of 6 weeks
	2	0·2	−10	Killed at end of 6 weeks
	6	0·3	0	

The two meals appear to be about equal in vitamin B content as 0·3 gm. in each case gave the desired results of the same weight at the end of the experiment as at the beginning. Using Sherman's (2) method of evaluation by units, the pigeon-pea meals are excellent sources of vitamin B, having about 1510 units of vitamin B per pound whereas he gives for cereals (whole grains, including embryo) a value of 800–1200 units per pound.

CONCLUSIONS.

The vitamin A and B content of the pigeon pea (*Cajanus indicus*) have been determined. The plant meal is a good source of vitamin A due probably to the large amount of green leaves in it, whereas the seed meal is a rather poor source. Both the plant and seed meals are excellent sources of vitamin B which is characteristic of other legumes.

REFERENCES.

(1) KRAUSS, F. G. (1921). The Pigeon Pea (*Cajanus indicus*): Its culture and utilization in Hawaii. *Bulletin No.* 46, *Hawaii Agri. Exp. Sta.*

(2) SHERMAN, H. C. (1926). *Chemistry of Food and Nutrition.* 3rd ed. Macmillan.

(3) SHERMAN, H. C. and MUNSELL, H. E. (1925). The quantitative determination of Vitamin A. *J. Amer. Chem. Soc.* **47**, 1639.

(*Received February* 21*st*, 1928.)

YIELD AND PLANT POPULATION IN SUGAR BEET.

By F. L. ENGLEDOW, M.A. and C. A. MAHER, B.A.,
School of Agriculture, Cambridge;
J. HUNTER SMITH, B.Sc. and H. RHYS WILLIAMS, B.Sc.,
Hertfordshire Institute of Agriculture;
H. FAIL, B.Sc. and F. RAYNS, M.A.,
Norfolk Agricultural Station.

(With Three Diagrams.)

CONTENTS.

§ I. Introduction.

THREE years of subsidised sugar-beet growing in England has made clear the chief agricultural features of the crop. Many of our soils suit it well; the climate is favourable; it fits satisfactorily into some of our typical rotations. With the 1928 crop will come into operation the first of the subsidy reductions. The consequential change in standard price per ton of beet—46*s.* instead of 54*s.* as in 1925–7—has aroused anxious interest in the likelihood that the crop will outlive the subsidy. What price the factories will be able to offer on termination of the subsidy is not yet known. It will, of course, be decided by world-prices of sugar. Values between 30*s.* and 35*s.* per ton have been tentatively suggested. It has been claimed, further, that any price which covers cost of production will make the crop an asset to English agriculture because of the benefit to following crops. Whatever the strength of this claim farmers are and will continue to be anxiously concerned about net monetary return per acre. Now this return is governed by three factors—cost of growing,

yield per acre, and price per ton. Costs of growing are not likely to alter substantially. Price per ton is considerably influenced by sugar content. The factories have devoted much effort to routine sampling and testing of deliveries but have not convinced farmers that their ascertainments are reliable. It may well be doubted whether any workable factory testing can be devised to ensure accuracy to 1 per cent. of sugar content. In short, valuation on sugar percentage appears somewhat impracticable. And further, the sugar content of a piece of beet is in general much more a reflection of soil, locality, and season, than of cultivation and manuring. In time, then, it may appear to the interest of all concerned to buy and sell beet simply on weight. Restriction would be necessary in respect of dirt tare and topping and it would be practicable and equitable to make a final price adjustment on average sugar percentage for the full factory campaign. Thus yield per acre, already the prime factor in net monetary return per acre and the factor essentially under the farmer's control, may before long gain in importance.

Broadly, manuring and cultivation are the controllable factors which govern yield. Use of fertilisers, preparation of seed bed, inter-cultivations, and lifting are rapidly taking the form of well-understood standard practices. The points of practice about which doubt remains are those which affect the plant population per acre, and it is universally recognised that this bears a most important relationship to yield per acre. Common agreement has not yet been reached as to seed-rate nor has its relation to plant population and thus to yield per acre, been explored. Attention has been freely given to the theoretical number of plants per acre represented by various combinations of distance between rows and singling interval. Continental practice ensures a denser population of plants than is common in our own fields. The relation between closeness of plants and both cost of cultivation and yield needs much closer attention. When definite distances between rows and between plants have been decided upon, yield per acre depends very directly upon the extent to which the theoretical "full plant" is secured. Even in the best of fields occasional gaps or "misses" occur in the rows. From point to point along every row the distance between one plant and the next fluctuates markedly. It may be that some men, at singling, are not very successful in adhering to the prescribed interval; or the horse hoe may cut plants out; or there may have been considerable gaps in the unsingled rows. Roots which have more than average space grow to more than average size, and thus there is a tendency towards "compensation" in yield for paucity of plants. But how frequent are the

gaps, how great the fluctuation in distance between plants, and how adequate the compensation, are matters determinable only by precise enquiry. Analogous enquiry has been made in cereal crops (*vide* (1, 2, 4, 5)). The results, coupled with observations on beet and mangold crops (*vide* (3)), have suggested the desirability of closely studying the plant population in fields of sugar beet. To examine a field crop plant by plant may appear, from the practical standpoint, no more than experimental refinement. But every root—or gap—counts in determining yield per acre; beet is a costly crop to grow even if only half a full plant be secured; and the future of the crop in England depends upon the average yield from our fields.

Preliminary investigations (*vide* (3)) made on the 1926 crop suggested the practicability of increasing returns by closer approach to a "full plant." It was therefore decided to conduct conjoint investigations in the counties of Cambridgeshire, Hertfordshire, and Norfolk.

§ II. An Outline of the Investigation.

The essential object was to ascertain the distribution of plants in typical fields of sugar beet; to trace the changes in plant population during growth, to assess the extent of fluctuation in closeness of plants from point to point along the rows, and finally to test the relation between the various gradations of population density and rate of yield in one and the same field. In addition certain causative agencies were studied and observations made upon the influence population density exercises on root size, sugar content, and other characteristics.

Six fields were studied, two in Cambridgeshire, three in Hertfordshire, and one in Norfolk. They will be referred to as Fields A–F. On some, certain periodic counts had to be omitted, but a sufficiency of data was obtained to delineate the essential features of life history. If growth progress could have been followed by periodic liftings and weighings much would have been added to the value of the work. Such an addition should find a place in any repetition of studies of this kind, for it is not uncommon for a piece of beet to start with a full plant and excellent promise and then to fail in yield on account of inexplicably poor root development.

In Table I are given the main agricultural features of the six fields. Further details of treatment and development are explained at appropriate points in later passages. A full account of experimental procedure will be found in Appendix I which is a copy of the working instructions adopted by the three experimental stations responsible for the investi-

gation. Studies of actual field crops involve an amount of work and a geographic dispersion which can be effected only by collaboration. In the present instance collaboration was singularly smooth. The full agreed working plan (Appendix I) may therefore be of some interest apart from the necessity of explaining experimental method and the possible value of detailed plans for similar studies in the future.

Table I. *Previous crop: manure and fertilisers applied in connection with the sugar-beet crop: numbers and dates of cultivations on the sugar-beet crop.*

	A	*B*	*C*	*D*	*E*	*F*
Previous crop	Wheat	Barley	Wheat	Winter oats	Sugar beet	Mustard
Dung before beet crop (per acre)	10 tons	15 tons	10 tons	20 tons	*	†
‡Fertilisers before sowing	3 cwt. K. 2 cwt. S.P. —	1½ cwt. S.A. 4 cwt. S.P. 1 cwt. M.P.	1 cwt. S.A. 2 cwt. P.S. —	1 cwt. S.A. 4 cwt. S.P —	6 cwt. C.D. — —	1 cwt. S.A. 3 cwt. S.P. 4 cwt. K.
Sowing	May 9	May 4	May 3	May 10	May 20	—
‡Fertilisers during growth (per acre)	2 cwt. N.S. May 18	2 cwt. N.S. June 8	1 cwt. S.A. June 17	¾ cwt. N.L. June 11	1 cwt. N.S. June 17	— —
Horse hoeing before singling	May 30 June 6	May 27 —	Nil —	June 6 —	June 9 —	— —
Singling	June 8	May 30	June 9	June 11	June 15	—
Hand hoeings	July 5 July 8	June 14 Aug. 13	June 8 July 9	Two —	July 5 —	— —
Horse hoeings	July 13 July 22 July 26 —	June 14 (Twice) July 6 —	June 22 July 21 — —	Three — — —	June 23 July 3 July 20 Aug. 4	— — — —
Lifting (date of beginning)	Oct. 17	Oct. 14	Nov. 22	Nov. 30	Oct. 28	Oct. 29

* Sugar beet in previous year had 20 tons farmyard manure and tops were ploughed in.

† Previous mustard crop had 10 tons farmyard manure per acre.

‡ S.A. = sulphate of ammonia; S.P. = superphosphate; M.P. = muriate of potash; N.S. = nitrate of soda; N.L. = nitrate of lime; C.D. = prepared compound sugar beet fertiliser; P.S. = 30 per cent. potash salts; K. = Kainit.

In each field one acre was chosen as being representative of the field as a whole, so far as could be judged. Counts of population density and root-weighings were made on sample lengths of row in this acre. One hundred sample points were selected. They were so arranged as to cover the acre regularly and to fall with equal frequency on the work of the four coulters of the drill. In all cases seeding was done with a four coulter drill. Diagrams I and II attached to Appendix I illustrate the arrangement of sample points. For the seedling-population counts the sample was a one-foot length of a row of plants. After singling it was a four-foot length. These lengths were determined by considerations explained in an earlier publication (*vide* (1), pp. 168–9).

At every sample point two samples, adjoining lengths of row and designated α and β, were drawn. The object of duplication was two-fold. Duplicate series of results (α and β) afford a check on reliability; further, the characteristics of short adjacent lengths of row are important evidence concerning the causes of irregularity in density of plant. This second consideration is treated at length in § III (*infra*). Statistical reliability of result is dealt with separately in Appendix II. It is there shown that in no case was the mean difference between the α and β series of values statistically significant. Moreover no correlation was found between the α and β series for any characteristic. It is thus needless, in presenting the main results, to separate the α and β series, and in all the periodic count tables the two series have been amalgamated.

In the paragraphs which follow results are presented in chronological order with a discussion of causative agencies. It is convenient to consider at this point the essential findings. In all the fields the seedling population showed swift and sharp density fluctuations from point to point along the plant rows. Low germination capacity and irregular distribution by the drill were the prime causes. At singling, irregularities in the seedling population and inconstancy in the mens' work produced, in all fields, a much smaller population of plants per acre than the theoretical maximum. The rates of yield from the various gradations of population density were of great interest. Lengths of row with few plants showed high average root size but low yield per unit area. In aggregate the thinly populated lengths represented a substantial diminution below the potential maximum yield per acre appropriate to soil and season.

§ III. The Seedling Population.

It is in sugar beet, of all our field crops, that a full, even plant is to be expected. In common with other root crops it is singled, only the most suitable fields are selected for it, preparatory cultivations and making of the seed bed are done with great care, and it is a spring crop. Further, it will be shown in later passages that the Continental insistence on full even plant as a guarantee of maximum yield, is strictly applicable to our own conditions. In examining the distribution of plant population in typical English beet fields, therefore, a high standard must be kept in mind. The spring of 1927 was unfavourable to most spring seedings. It was possible to prepare good seed beds but drought and drying winds made germination slow. In the case of sugar beet relatively deep sowing with tight rolling succeeded best, for contact of the seed with moist soil was ensured. Depth of sowing varies from point to point in a field as

does tightness of rolling. It was this that partly induced irregularity in rate of germination over the face of the field. A second chopping-out was necessary in some fields to remove plants which appeared shortly after the normal singling. But, as will be shown, there were other agencies to which irregularity in the seedling population was attributable.

Table II. *Frequency distribution of number of seedling plants per one-foot of row: frequencies are expressed as percentages: for α and β series combined,* i.e. 200 *samples per acre: second count* (vide *row* 5, *Table IV*).

Field	Number of plants per foot																			
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18*	Av.
A	10·0	9·5	7·0	6·0	6·0	10·0	5·5	5·0	6·0	5·5	6·5	4·0	5·0	2·5	3·0	3·5	1·0	0·5	3·5	6·7
B	2·5	2·0	6·5	6·5	5·0	6·5	9·5	9·5	6·0	7·0	8·0	3·5	4·5	5·0	3·0	3·0	2·0	3·0	7·0	9·8
C	3·0	9·5	9·0	10·0	11·5	8·5	13·0	8·0	3·0	6·5	5·5	2·0	3·0	3·5	2·5	1·5	—	—	—	5·8
D	13·5	11·5	15·5	16·5	11·0	8·0	6·0	5·5	2·5	3·0	2·0	1·5	1·0	—	1·0	—	0·5	—	1·0	3·9
E	11·5	8·5	12·5	12·5	8·5	12·0	6·5	6·5	3·0	3·0	4·5	6·0	0·5	1·5	1·0	—	1·5	—	0·5	4·9

* Frequencies for 18 per foot and over are included to reduce the size of the table.

Counts of seedling plants were made on Fields *A* to *E*. They disclosed very marked irregularity. Table II gives the frequency distribution of number of plants per foot immediately before singling. It will be seen that on Fields *A*, *D* and *E* at least 10 per cent. of row was entirely devoid of seedling plants, while the proportion of the field with 0 or 1 plant per foot was about 20 per cent. The frequency classes in this table show merely total numbers of plants per foot. It is important to bear in mind that within any one foot the plants were very irregularly distributed. Thus in a field such as *E*, with over 50 per cent. of the area having only from 0–4 plants per foot of row, the prospect of a reasonable approach to full plant at maturity was already wrecked before singling. As a fact, at lifting, the plants on this field numbered only 65 per cent. of the full plant proper to the spacing adopted. It is unnecessary to dwell on the form of the distributions in Table II, but it is a remarkable fact that they represent a wider fluctuation than is commonly found in fields of winter wheat. Fluctuation in seedling wheat plants is fully discussed in an earlier paper (*vide* (4)).

Another striking feature of Table II is the wide range, as between fields, in average number of seedling plants per foot for the whole field. The values for fields *A*–*E* are from 9·8 to 3·9 plants per foot. Many circumstances no doubt explain these inter-field differences. One is seed rate, and it may be seen from Table IV (row 2) that on Field *D* which received the lowest seeding (10 lb.) there was the thinnest seedling plant. It appears quite safe to assert that under-seeding is one of the weaknesses

of beet growing in this country. In mangolds, which are notoriously gappy, the fault and the sacrifice of yield it involves, are still more serious. To expect men to transmute a highly irregular, gappy, seedling population into a full and even field of singled plants is unreasonable. The peculiar difficulty of the workmen's task at singling is clearly illustrated in § IV (*infra*).

In seeking the causes of irregularity of seedling populations three agencies must be examined—seed, tilth, and drill. Knowledge of germination of beet seed is limited. How far laboratory tests reflect behaviour in the field is a first point awaiting enquiry. Another matter of importance is size of "seed" (fruits). Typical samples may be sieved into grades between 2 mm. and 5 mm. Now the cup of the drill may pick up very fluctuating numbers of fruits (and therefore of actual seeds) from such a mixture of sizes. In this fact undoubtedly lies a prominent cause of irregularity in seedling population. Fruit ("seed") size has, further, an important bearing on germination. Mr A. Eastham, D.S.O., M.C., Chief Officer of the Official Seed Testing Station, has very kindly given access to results of an enquiry into this matter. Further investigation, now in progress, will be necessary for precise ascertainment of the facts. But it is already clear that, as suggested by the older work of Kiehl, very small fruits give low germination (as percentage of fruits or clusters). More careful grading of seed may thus be expected to bring improvement. Official Seed Testing Station returns show that the average germination of sugar-beet seed is about 80 per cent. (of fruits or clusters). If, then, every foot of row were regularly seeded with x true seeds, there would be fluctuation in number of seedling plants per foot of an order represented by the expansion of $(\frac{2}{10}+\frac{8}{10})^x$. Fluctuation in number of seeds deposited per foot would naturally add to this irregularity. The dangers of light seeding are therefore patent. It is suggested that 17 lb. per acre is the seeding in general desirable with present day commercial seed (with rows at 16–18 inches apart). The 10–12 lb. sometimes applied is certainly too low.

No attempt will be made here to estimate the influence of tilth on seed distribution. It is an intricate problem complicated by the fact that even the 80 per cent. germination obtained in laboratory test independently involves irregularity of plant. The problem has been fully studied in the case of cereals (*vide* (4), pp. 28–32). It was shown that inherent defects of drill action, far more than tilth, were responsible for irregular deposition of seed. Proof rested largely on absence of correlation between numbers of seeds deposited on adjacent short lengths of

row. In this connection absence of the corresponding correlation for seedling plants is significant (*vide* Appendix II (*infra*)).

Drill action may be faulty in two respects. For any one coulter the number of seeds deposited per foot of row may fluctuate sharply. Experimental proof that such fluctuation is inherently associated with typical cup drills, sowing corn, has been given (*vide* (4)). Corresponding tests have not been made with root drills, but it is believed they would demonstrate even more marked faults in delivery. A second common fault of the drill is irregularity of deposition by the separate coulters (cf. (4), pp. 32–8, for corn drills). In connection with the five beet fields on which the seedling population was counted, it was possible to give the average density of plant from the sowings of the separate coulters.

Table III. *Average number of seedling plants per foot (α and β series combined) for rows sown by the separate coulters of the drill.*

Field	Coulter number			
	1	2	3	4
A	5·96	4·82	9·00	6·90
B	8·90	11·60	9·40	8·90
C	6·34	5·86	6·60	5·04
D	4·82	2·88	3·54	4·22
E	4·72	5·12	5·14	4·38

The values are given in Table III. Tests of significance show that, for every drill, at least one inter-coulter difference is of such magnitude as not to be attributable to errors of sampling. Thus for Field *C* coulters 1 and 4 differ by 1·30 plants per foot while 3 and 4 differ by 1·56 plants per foot. The appropriate probable error of difference between two means is 0·40 so that the margin of sampling error may be taken as 1·21 plants per foot.

These results suggest that root-drills, like corn-drills, are doubly imperfect. Individual coulters deposit inconstantly over successive short periods of time, and the average deliveries of coulters of one and the same drill over a considerable period of time are unequal. No amount of care in preparing the seed bed can counteract inherent drill deficiencies which, together with seed germination, are factors in limiting the yield of sugar beet.

§ IV. Singling to Maturity.

For simplicity of presentation, detailed consideration of population changes is deferred to § V (*infra*) in which yield is represented as the culmination of quantitative history. The essential features of population

between singling and maturity are simple. Seedling plants were thinned to degrees approximately indicated by the following values:

Field	*A*	*B*	*C*	*D*	*E*	*F*
Average number of plants per 4 ft. of row before singling	26·8	39·2	23·2	15·6	19·6	?
Average number of plants per 4 ft. of row after singling	4·0	4·2	3·8	3·5	4·4	2·9

Only very slight changes occurred after singling, the population remaining substantially unchanged up to maturity. There were fluctuations in spacing in the singled rows but these are considered in § VI (*infra*).

It was intended to ascertain how closely separate men at singling adhered to the inter-plant spacing ordered. Appropriate observations proved difficult for two reasons. Workmen, knowing themselves to be under constant observation, do not work normally. Further, the result attained depends not only on the man's skill and care but on the spatial irregularities in the rows of seedling plants on which he works. Preliminary observations, made at one station are however, of some interest. Four men *P*, *Q*, *R* and *S* on piece rates singled the census acre, their tasks being so allotted that each did four of the sixteen rows from which census samples were drawn. Their tasks and performances may be specified as follows:

Workman	Av. no. of plants per 4 ft. before singling	Av. no. of plants per 4 ft. after singling
P	23·16	3·87
Q	22·00	3·45
R	22·88	4·14
S	24·80	4·62

All the men were ordered to single to ten inches (*i.e.* 4·8 plants per 4 feet of row). Their results were by no means alike and none attained the specified average density of plant. This latter fact is, naturally, in part attributable to irregularities in the unsingled plant population. Further investigation will be necessary to make a firm ascertainment of the significance of personal idiosyncracy and skill of individual workmen. The available data is, however, sufficient to indicate the difficulties imposed on the men by spatial fluctuation in the seedling plant. For instance, one man, *S*, in singling his four rows, dealt with a varying situation specified in a general way by the values:

Row number	1	2	3	4
Average number of plants per 4 ft. before singling	24·0	23·6	34·4	17·2
Average number of plants per 4 ft. after singling	5·0	4·4	4·8	4·1

It is seen, even from the average values, that rows 3 and 4 presented very different tasks which, evidently, were skilfully performed. But

these average values are silent as to the length-to-length irregularities of seedling population along one and the same row. Singling is recognised to be a difficult and costly operation. Upon its success a full plant—one essential for close approach to maximum possible yield—is directly dependant. From the evidence adduced on irregularities in the seedling population it appears that the cost and success of singling are largely determined by germination of seed and mechanical efficiency of the drill.

§ V. The Mature Crop.

The most informative way of assessing the attributes of the mature crop is by surveying the outlines of crop life. Table IV, a record of periodic census counts and connected data, gives a chronological résumé. This is not analytical, for it is based on per acre averages for the six fields. The relation between rate of yield and gradations of spacing within the individual fields is discussed later. It is convenient to refer to entries in Table IV by the row number (left-hand column of table).

All the fields were drilled (row 1) within a seventeen day period in May, seed rate varying from 10–17 lb. (row 2) and distance between coulters ranging from 18 to 21 in. (row 3). These inter-field differences naturally occasion differences in average density of the seedling population. Actually, average numbers of seedling plants (row 5), are reasonably in accordance with expectation, based on seed rate and coulter distance save for Field *E*. On that field, had effective germination been as for Field *A*, there would have been an average of 7·6 plants per foot of row. The difference = 7·6 − 4·9 = 2·7 (expected-observed) is statistically significant. Thus some circumstance made Field *E*, or the seed sown on it, less favourable to germination than Fields *A*–*D*. Observations at sowing suggested no soil circumstance so that low seed-germination may have been the cause. Two counts were made between germination and singling on Fields *B* and *C* (rows 4 and 5) and from these it is evident that plant casualties were not serious during the period.

Singling took place (row 6) on all fields early in June, the specified interval being 10 in. on four fields, seven on one, and nine on another (row 7). Population counts were made on Fields *A* and *C* during June and July (rows 8, 9 and 10) and on *A*, *B*, *D* and *E* in mid-August (row 11). These clearly show that from singling in June to mid-August, loss of plants was negligible, while the count at lifting (row 13) makes it clear that constancy of plant population was maintained to maturity. In Field *A* there is an apparent exception in the decrease from 5·2 to 4·2

value per acre: all values are for series α and β combined, i.e. 200 *samples per acre.*

Row no.		Field A	B	C	D	E	F
Sowing and germination							
1	Date of drilling	May 9	May 4	May 3	May 10	May 20	May 4
2	Seed rate (lb. per acre)	14	17	15	10	15	10
3	Width between rows (coulters)	19 in.	20 in.	18 in.	21 in.	20 in.	21 in.
4	Average number of seedling plants per foot ...	—	9·4	5·8	—	—	—
	Date of count (1st count)	—	May 24	May 27	—	—	—
5	Average number of seedling plants per foot ...	6·7	9·8	5·8	3·9	4·9	—
	Date of count (2nd count)	June 7	May 30	June 8	June 9	June 10	—
After singling							
6	Singling date	June 8	June 5	June 9	June 11	June 15	?
7	Singling interval ordered	9 in.	10 in.	10 in.	10 in.	7 in.	10 in.
8	Average number of plants per 4 ft.	4·9	4·7	4·0	—	—	—
	Date of count (3rd count)	June 22	June 11	June 10	—	—	—
9	Average number of plants per 4 ft.	5·2	4·3	3·9	—	—	—
	Date of count (4th count)	July 8	June 23	July 4	—	—	—
10	Average number of plants per 4 ft.	4·2	4·3	3·8	—	—	—
	Date of count (5th count)	July 18	July 24	July 25	—	—	—
11	Average number of plants per 4 ft.	4·1	4·2	—	3·6	4·7	—
	Date of count (6th count)	Aug. 9	Aug. 14	—	Aug. 15	Aug. 14	—
At lifting							
12	Date of lifting	Oct. 17	Oct. 17	Nov. 22	Nov. 30	Oct. 28	Oct. 28
13	Average number of plants per 4 ft. of row (7th count)	4·0	4·2	3·8	3·5	4·4	2·9
14	Average weight of a single beet (topped and washed) in lb.	0·90	0·95	0·88	0·86*	0·70*	0·99
15	Average weight of top per plant (lb.)	—	0·95	0·85	1·05	0·99	—
16	Number of plants per acre	27,580	27,312	27,298	21,718	29,011	17,735
17	Number of plants per acre corresponding to row width and singling interval ordered	36,668	31,363	34,848	29,853	44,799	29,853
18	% of full possible plant obtained	75·2	87·1	78·3	72·7	64·6	59·4
19	Average distance between plants	12·0 in.	11·5 in.	12·8 in.	13·8 in.	10·8 in.	16·8 in.
20	Singling interval ordered	9 in.	10 in.	10 in.	10 in.	7 in.	10 in.
21	Yield of top in tons per acre (by sampling) ...	—	11·6	10·3	10·2	12·8	—
22	Yield of washed and topped beet in tons per acre (by sampling)	11·1	11·5	10·7	8·3*	9·1*	7·9
23	Average % of sugar (by sampling)	18·1	18·9	16·9	17·5	16·3	16·4
24	Value per ton at 1927 crop prices	60*s.* 6*d.*	62*s.* 6*d.*	57*s.* 6*d.*	59*s.* 0*d.*	56*s.* 0*d.*	56*s.* 3*d.*
25	Monetary value per acre (from sampling data) in pounds sterling	33·5	35·9	30·8	24·5	25·5	22·1

* In these cases it was not possible to wash the roots: they were merely hand cleaned. The produce of the acre, so cleaned, was weighed before despatch and then tared for dirt at the factory. By using the ratio of these weights a correction for dirt tare was applied to the recorded weights of the samples.

plants per four feet of row between July 8 and July 18 (rows 9 and 10). Drought induced a number of late germinations in this field and a second "chopping" out had to be made on July 10 to remove seedlings which had appeared between the singled plants. This accounts for the apparent exception. The evidence from five fields (*A*–*E*) therefore shows that plant population remains constant from singling to maturity. It follows that fluctuations in population density from point to point along the rows at maturity—the subject of discussion in § VI (*infra*)—reflect directly the fluctuations present immediately after singling. These latter, as explained in §§ III and IV have their origin mainly in defective deposition of seed by the drill. To drill defects, therefore, are traceable the chief irregularities in final plant and the yield-loss they occasion.

It is important to notice the extent to which, in every field, the actual plant population (row 16) approached the theoretical "full plant" (row 17) based on coulter-distance and specified singling-interval. The relationship, expressed as a percentage (row 18), ranged from 87 per cent. to 59 per cent. The true significance of these values can be gauged only from consideration of the fluctuations of density along plant rows by which they are determined (§ VI *infra*). A similar reservation applies to the spacing interval, specified (row 20) and attained (row 19).

Average size of root (row 14) while of great importance cannot, with the data at command, be treated analytically. It is governed by spacing and by the unknown factors, soil-fertility and damage by disease. Not unexpectedly Field *F*, lowest in plant population (row 16), is highest in root size (row 14), and for Field *E* the converse is true.

Yield per acre (row 22) may for the present be treated as the product of average root-size and number of plants per acre. Fields *A*, *B* and *C* (in Cambridgeshire, Hertfordshire and Norfolk respectively) had approximately the same yield of about 11·0 tons per acre; their populations, too, were almost identical. The other three fields (*D* and *E* in Hertfordshire, *F* in Cambridgeshire) gave lower yields (row 22). Comparison of Fields *C* and *D* reveals a small difference in average root-size (0·88 and 0·86 lb.) but a rather emphatic difference in population (27,300 as 21,700) in consequence of which the yields differed by 10·7 – 8·3 = 2·4 tons per acre. Root-size was at its highest on Field *F* but a very sparse population resulted in the low yield of 7·9 tons. Field *E* is of special interest. A singling interval of 7·0 in. was attempted, an average of 10·8 in. being attained. The plant population was greater than on any other field and this, no doubt, partly explains the low average root-size of 0·70 lb. It is not improbable that fertility was relatively low. This

possibility brings to notice the special importance of dense population (within practical limits) on very light soil or land for other reasons not favourable to strong root development.

One object of investigation was an analysis of the influence of spatial fluctuation upon root-size and the connected attribute sugar content. Broadly, for the produce of any one field, the larger roots are the lower in sugar content. When, at maturity, census samples were drawn, they were grouped according to number of plants per sample (*i.e.* 4 foot length of row). From these groups, after weighing, were drawn samples for determination of sugar content. For three of the fields there was evidence of orderly relation between root-size and sugar content. Thus for Fields *A* and *F* the values were:

No. of plants per 4 ft.	Field *A* Av. wt. of root	Field *A* Sugar %	Field *F* Av. wt. of root	Field *F* Sugar %
0	—	—	—	—
1	1·05	17·8	1·75	16·0
2			1·20	16·0
3	1·09	17·4	1·00	16·4
4	0·93	17·4	1·00	16·3
5	0·84	19·0	0·80	16·7
6 or more	0·73	19·6	0·70	16·4

The *prima facie* expectation of increase in sugar percentage with decrease in root-size occasioned by diminishing spacing, is on the whole suggested by these results. Unfortunately evidence was not obtainable from the other fields because sugar analyses on the α and β series of samples were not in agreement. The reasons for this lack of agreement are not clear. In all other characteristics the α and β series showed very high concordance. The partial evidence from this investigation suggests that the fluctuations in sugar content arising from fluctuation of interplant spacing in any one field are not of an order to have agricultural significance.

"Top" were weighed as well as roots. The values, while displaying fluctuations analogous to those of root weight (§ VI *infra*) are not of special interest. For the complete acres, average top-weights are given in rows 15 and 21 of Table IV. In relation to the corresponding root-weights they are considerably higher than the values commonly quoted. The probable reason for this is that the tops were weighed absolutely fresh, *i.e.* before any significant loss of water.

§ VI. Yield and Population Density.

The essential purpose of the investigations here described was to determine the extent of spatial fluctuation in typical beet crops and its influence on yield per acre. As, on the six fields, population remained

substantially unchanged from singling to lifting, it is sufficient to discuss fluctuation in the mature population only. Table V shows, for the six fields in turn, the nature of fluctuations in population density (as number of plants per 4 feet of row) together with relevant yield data.

Table V. *For all six fields: the gradations of plant population density at lifting and the corresponding values of percentage frequency of occurrence, rate of yield per acre, root-size, and cash return per acre (plant population density is expressed as number of plants per 4 feet of row).*

No. of plants per 4 ft. (1)	Av. plant interval (in.) (2)	% of acre (3)	Yield per acre (tons) (4)	Av. wt. of a root (lb.) (5)	Cash value per acre £ s. d. (6)
Field A					
0	—	2·5	nil	—	—
1	48	2·5	5·1	1·05	15 10 0
2	24	3·5			
3	16	23·5	10·1	1·09	30 11 0
4	12	27·5	11·5	0·93	34 12 0
5	9·6	32·0	13·0	0·84	39 4 0
6	8	8·5	13·5	0·73	40 19 0
Average	12	—	11·1	0·90	33 10 0
Field B					
0	—	—	—	—	—
1	48	0·5	6·4	1·33	20 0 0
2	24	2·0			
3	16	18·5	9·4	1·08	29 8 0
4	12	41·5	11·4	0·97	35 12 0
5	9·6	33·5	12·9	0·89	40 6 0
6–8	7	4·0	14·6	0·83	45 12 0
Average	11·5	—	11·5	0·95	35 18 0
Field C					
0	—	1·5	nil	—	nil
1	48	2·0	7·4	1·25	21 6 0
2	24	9·0			
3	16	25·5	10·3	1·06	29 12 0
4	12	35·5	11·0	0·85	31 12 0
5	9·6	22·5	12·3	0·76	35 7 0
6	8	3·5	13·8	0·69	39 14 0
7	6·8	0·5			
Average	12·8	—	10·7	0·88	30 16 0
Field D					
0	—	3·5	nil	—	nil
1	48	7·0	3·7	1·31	10 18 0
2	24	19·0	7·4	1·31	21 16 0
3	16	20·5	8·3	0·99	24 10 0
4	12	21·0	9·0	0·80	26 11 0
5	9·6	20·5	10·1	0·74	29 15 0
6	8	6·0			
7	6·8	2·0	11·9	0·68	35 3 0
8	6	0·5			
Average	13·8	—	8·3	0·86	24 10 0

Table V (*continued*).

No. of plants per 4 ft. (1)	Av. plant interval (in.) (2)	% of acre (3)	Yield per acre (tons) (4)	Av. wt. of a root (lb.) (5)	Cash value per acre £ s. d. (6)
Field E					
0	—	—	—	—	—
1	48	0·5	6·2	1·10	17 7 0
2	24	6·0			
3	16	18·5	7·8	0·89	21 7 0
4	12	25·0	9·2	0·79	25 15 0
5	9·6	31·0	9·6	0·66	26 18 0
6	8	14·5	10·0	0·57	28 0 0
7	6·8	3·5	10·4	0·50	29 2 0
8	6	1·0			
Average	10·8	—	9·1	0·70	25 10 0
Field F					
0	—	11·0	nil	—	nil
1	48	8·0	4·9	1·75	13 13 0
2	24	23·0	6·7	1·20	18 15 0
3	16	22·0	8·3	1·00	23 8 0
4	12	22·0	11·1	1·00	31 5 0
5	9·6	10·0	11·1	0·80	31 5 0
6–8	7	4·0	13·9	0·70	39 1 0
Average	16·8	—	7·9	0·99	22 2 0

It will be observed that population density ranges in value from 0 to 6 or more plants per 4 feet of row. Some 5 plants per 4 feet, *i.e.* a spacing of just under 10 in., is the commonly agreed optimum; it was the singling interval attempted on all fields save *E*. Inter-field differences in fluctuation are strongly marked. In Field *B* 93·5 per cent. of the samples, *i.e.* 93·5 per cent. of the whole field, had 3, 4 or 5 plants per 4 feet of row; Fields *A*, *C* and *E* come next in regularity of plant; Field *D* and still more Field *F* show marked irregularity. Indeed 11 per cent. of Field *F* is entirely devoid of plants while no less than 42 per cent. of it has 2 or less plants per 4 feet of row. Well-marked, localised, fluctuation of population density from point to point was clearly, therefore, characteristic of these six fields. That similar fluctuation characterises the English sugar-beet crop in general is suggested by careful observation.

The dependence of root-size on population density may be noticed next. In column 5, Table V, are given the average weights of root for aggregated samples each of 1, 2, 3, ... plants per 4 feet in turn. The values are striking. For every field they show a steady decrease in root-size with increase in population density. A few unimportant exceptions disturb some of the sequences, *e.g.* Field *A* (1·05, 1·09, 0·93, ...). These are attributable to the low reliability of average root-size for the extremes of population density.

Rate of decrease of root-size is far less rapid than corresponding rate

of increase in number of plants per 4 feet. Consequently yield per 4 feet must necessarily rise with increasing density of population. It is evident from column 4 of Table V that, for every one of the six fields, average rate of yield per acre from unit lengths of row is closely related to density of population. Actually the correlation between number of plants per 4 feet and yield of roots per 4 feet is in all cases positive and of the order of 0·5 which, being based on 200 samples per field, is statistically significant. Positive correlations but of the order of 0·6 to 0·8 were correspondingly found in the case of field crops of wheat (*vide* (5), pp. 326–7). Fields *A–F* were typical of the sugar-beet crop. Their spatial constitution (Table V, columns (1) and (3)) and the components of their yields (column (4)) as well as of the monetary return from them (column (6)) appear to justify the conclusion that spatial fluctuation characteristically limits the profit from the crop. It appears now to be generally agreed that one plant in every 10 in. of row is the ideal for English conditions. This corresponds to 4·8 plants per 4 feet. It may perhaps be inferred, therefore, that the maximum crop appropriate to soil, season and level of fertility on any field is the yield from the aggregate short lengths of row carrying about 5 plants per 4 feet. On this basis maximum possible and actual monetary returns from the six fields may be thus compared:

	Actual monetary return per acre			Maximum possible return per acre		
Field	£	*s.*	*d.*	£	*s.*	*d.*
A	33	10	0	39	4	0
B	35	18	0	40	6	0
C	30	16	0	35	7	0
D	24	10	0	29	15	0
E	25	10	0	26	18	0
F	22	2	0	31	5	0

It would not be proper to insist upon the absolute values employed in this comparison nor is it permissible to assume that a more full and even plant would call for no greater outlay. But there appears clear evidence that on all the fields monetary return was significantly limited by defects in population density. These defects are not irremediable, for in great measure they have their origin in the seed and the seed drill.

The form of analysis here employed—by aggregation of samples with a common number of plants—calls for critical consideration. It may be conceived that the association between number of plants and yield per unit length is indirect rather than of the nature of cause and effect. Variations in soil, in incidence of damage, and in other factors, might be such that, while limiting the number of seeds sown and plants

surviving on any short length of row, they also limited individual plant development. On "good patches" both population density and root development might be promoted. Soil and damage factors would then be primarily or even solely the determiners of yield. This question has been closely investigated in similar analyses of corn crops (*vide* (4), pp. 28–32). All the tests it appeared possible to apply, supported the conclusion that yield per unit length and number of plants per unit length were directly associated; that they were, in fact, of the nature of cause and effect. Proof rested largely upon the relation between adjoining (α and β) samples in the row. If soil and damage factors were primarily responsible, as in the hypothesis outlined above, adjoining samples should be correlated. Otherwise, it would be necessary to postulate the more or less exact coincidence of soil "patches" with the separate members of a pair of adjoining samples. Correlations were evaluated ($\gamma_{\alpha\beta}$) for number of plants per sample at the various counts and for yield of roots per sample. Some were positive, some negative, none was significant in terms of its probable error. Direct connection between population and yield per unit length of row appears therefore to be proved in the case of these six beet fields as, similarly, it was proved for fields of wheat and barley.

English beet growers, as a body, have made most praiseworthy progress with a crop which but a few years ago, was entirely new to them. To urge that their work should be substantially improved so as to secure more full and even plant populations is to espouse the claims of what may appear super-excellence. But the new crop is still on trial. It has to bear the grievous burden of a disappearing subsidy. Greater yield per acre is its only hope and this, it is believed, is to be realised mainly through a full and even plant.

It is a pleasure to acknowledge the kindness and helpful interest of all those who placed their fields at the disposal of the investigators.

APPENDIX I.

Details of Census Procedure.

§ I. *Object.*

To ascertain the extent of fluctuation in the distribution of plants in a sugar-beet crop, its causes, and its influence on yield per acre of roots and of sugar.

§ II. *Determinations.*

All counts and weighings of plants will be done on sample lengths of row as later explained.

The regular data to be collected is:

(*a*) The number of plants per unit length of row immediately before singling.

(*b*) The rate at which the seed germinates and the loss in plant produced by horse hoeing before singling, are of interest. If time allows one or two counts before (*a*) might profitably be made.

(*c*) The number of plants per unit length of row immediately after singling.

In this count the number of "doubles" should be recorded and the doubles reduced to singles as each sample is counted. To leave doubles to grow to harvest would make the results less reliable.

(*d*) The number of plants per unit length after the last horse hoeing.

If time allows more than one count may be made between singling and the last horse hoeing.

(*e*) The number of plants per unit length of row at harvest.

(*f*) The yield of washed and topped roots per unit length of row at harvest; if possible, the yield of top also.

(*g*) The sugar-content at different gradations of spacing. For this the samples will be grouped into five equal parts, *e.g.* all samples with from 0–2 plants per 4 feet, all with 3–4, and so on. This grouping cannot be decided until the result of (*e*) is known.

(*h*) The actual total yield for the experimental acre (described below) from which the samples are drawn.

(*j*) The average sugar-content for the experimental acre.

(*k*) The average yield per acre from the whole area of which the experimental acre forms part (as a check).

(*l*) The average sugar-content for the whole area of which the experimental acre forms part (as a check).

§ III. *Observations.*

A proper understanding of the experimental results will be possible only if the agricultural and other circumstances influencing the crop are kept under constant observation and carefully recorded.

Observation must include, among other things:

(*a*) Agricultural notes on all operations such as seed-bed preparation and sowing conditions.

(*b*) The dates of all operations, *e.g.* singling and of all counts mentioned in § II above.

(*c*) The nature, extent, and date of incidence of all damage and disease.

(*d*) The progress of growth, *e.g.* date of germination, date when plants in general have four leaves, etc. and also marked effects of drought or other weather conditions.

§ IV. *Growing the crop.*

(*a*) This experiment is an endeavour to assist farmers. It is therefore of great importance to ensure that all the circumstances of growing are strictly comparable with those obtaining on reasonably good farms in the locality. A "show" piece of work and a yield far above the average of the district are thus not to be sought.

(*b*) There should be sown an area of not less than three acres. Upon this an experimental acre will be chosen as later explained. To choose the experimental acre from some lesser piece than three acres is undesirable on the ground that a small area, *e.g.* $1\frac{1}{2}$ acres, cannot be handled in the ordinary agricultural way.

(*c*) The three acres should be used for no other experiment, *e.g.* manurial treatment.

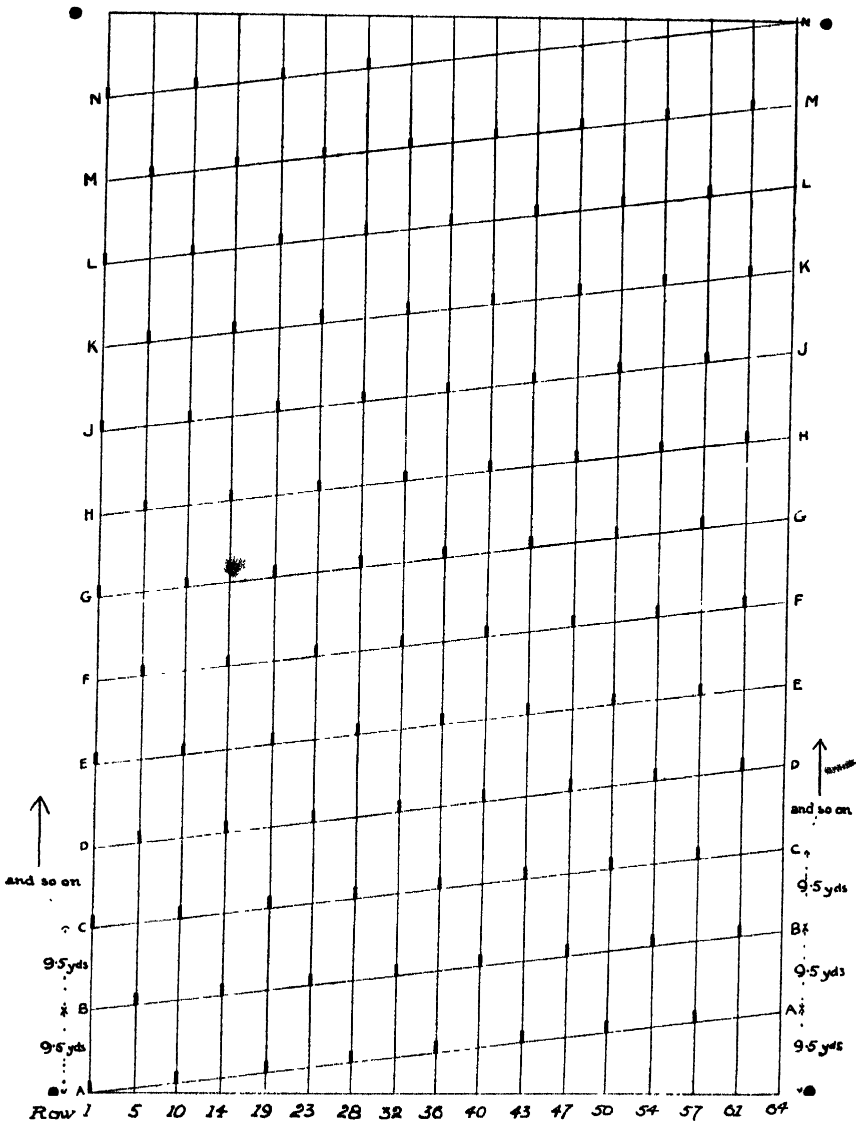
(*d*) Preparation of the land, seed rate, date of sowing, variety of seed, date and method of singling and all other matters of husbandry (save those specifically mentioned below) should be governed by local custom.

(*e*) If possible, sowing should be by a 4-coulter drill as this simplifies sampling arrangement. The explanations which follow are based upon such a drill. They can, however, be readily modified to meet the case of a 2-coulter or (less readily) a 6-coulter drill.

(*f*) For the plans and explanations below an interval of 22 in. between rows is assumed. Modification for the case of some other interval can easily be arranged.

(*g*) In singling, a distance of 10 in. from root to root is desirable.

DIAGRAM I.



The Distribution of Samples. The samples are located on coulter rows 1, 5, 10, ... as indicated.

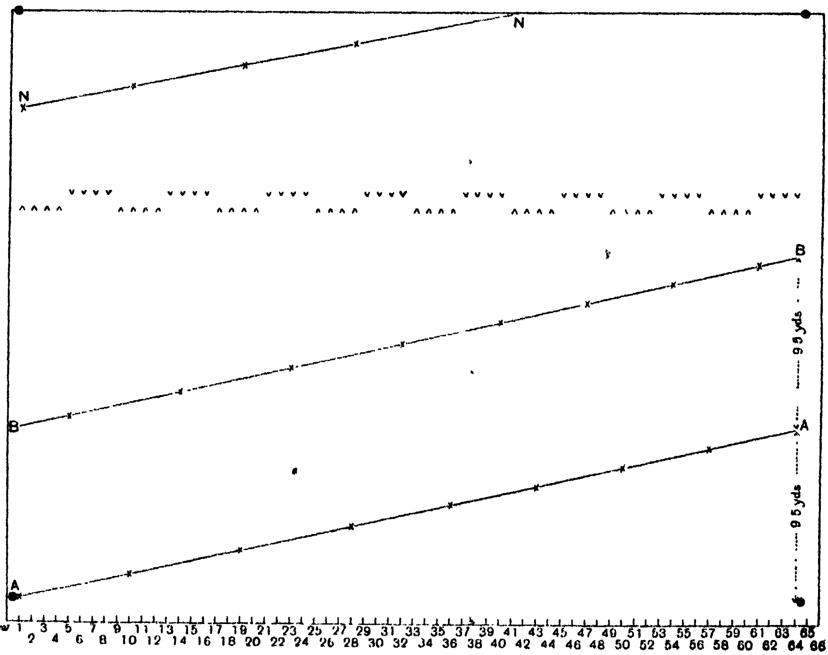
§ V. *The arrangement of the samples.*

(*a*) The experimental acre must be so located on the 3-acre piece as to be as fairly representative as possible of the average soil conditions of the whole area.

(*b*) Its width (measured across the rows) must be such as to include exactly 8 bouts (8 up and 8 down) of a 4-coulter drill, *i.e.* 64 rows. Consequently for rows sown at 22 in. apart its width will be 64 × 22 in. = 39·1 yd.: therefore its length must be 4840/39·1 = 123·8 yd.

(*c*) The 64 rows will be permanently known as row 1, row 2, ... row 64 (see base line of Diagram II).

DIAGRAM II



Direction of Drilling for Rows 1–64.

(*d*) Diagram I shows the scatter of the samples. These are arranged on 13 oblique "traverses" marked *AA*, *BB*, *CC*, ... (excluding *I*). Traverses *AA* to *MM* have 8 samples each (96 in all): traverse *NN* has the remaining 4 (total 100 samples).

(*e*) Samples are taken from rows 1, 10, 19, 28, ... for traverses *AA*, *CC*, ... and from rows 5, 14, 23, 32, ... for the alternate traverses *BB*, *DD*, ...

This arrangement besides giving a uniform scatter of samples over the experimental acre ensures that exactly 25 samples are drawn from the rows sown by each of the four coulters of the drill. To ensure that the system is fully understood this fact should be verified by examination of Diagrams I and II. In Diagram II the exact details are given for traverses *AA*, *BB* and *NN* and the direction of the drill for the sowing of all the 64 rows is shown. The key on p. 600 is a guide to this.

(*f*) The traverse lines *AA*, *BB*, ... divide the long sides of the acre into 13 equal parts. Thus (with rows at 22 in.) the distances *AB*, *BC*, ... along either side should be $123{\cdot}8/13 = 9{\cdot}5$ yd. (approx.).

(*g*) Remember that the coulters of the drill are numbered 1 to 4 from left to right of a man walking behind the drill.

§ VI. *Marking the acre and the samples.*

(*a*) Decide the approximate site of the experimental acre while the seed bed is being prepared. When the drill reaches one side of this insert two poles (see ● on left side of Diagram I). These must be 123·8 yd. apart and must stand in a wheel mark between two bouts of the drill.

(*b*) The first seed row beyond this wheel mark will be row 1. Count 64 rows from and including this and insert two more poles (Diagrams I and II) between the 64th and 65th rows. Ensure a rectangular shape in finally positioning the corner poles.

(*c*) Carefully note and record the direction of the drill in sowing row 1, and row 64 to ensure agreement with the arrows in Diagram II which mark the direction of the drill for the 8 bouts involved (8 up and 8 down).

(*d*) To ascertain the position of the samples for the counts before singling proceed thus: Join pole *A* at the lower left corner of Diagram I by a cord running across the drills to the opposite pole (and therefore corresponding to the base line of Diagram I).

Measure up from this latter pole 9·5 yd. to the point marked *A* on the right-hand boundary line of Diagram I. Join this point to the lower left corner pole by another cord.

On row 1 the first sample will be, as shown, where this row cuts the base line. The others will be at 19 yd. intervals up the row as shown and can be quickly found by using a 19-yd. cord.

On row 10 the first sample will be at the point where this row cuts the cord *AA*. The remainder come at 19-yd. intervals. Proceed similarly for rows 19, 28, 36, ...

Next set out a cord on *BB*, and, in the way explained, find the

positions of the samples on rows 5, 14, 23, ... In making the first count it is desirable simply to mark the ends of each sample by temporary pegs, then count the plants, remove the pegs, and proceed to the next sample. Count all the samples on a row in turn, then begin on the next row.

(*e*) For the first count made after singling, permanent pegs should be inserted at the ends of every sample. A suitable peg is a piece of lath, 1 ft. long and about 1 in. wide. Insert it in the row (its width across the row) and press in so that only about 3 in. protrudes. If desired, long conspicuous pegs may be put in when it is considered that they will not interfere with horse hoeing.

(*f*) For *all* purposes the rows must be referred to as Nos. 1–64 (see Diagram II). Samples will be designated with the letter of the traverse and the number of the row, *e.g.* *A* 43 or *E* 10.

§ VII. *Size of samples.*

(*a*) In all counts and in weighing, every sample should be duplicated, *i.e.* starting from the end determined as in § VI two consecutive sample lengths should be marked out and separately counted and recorded. These will be known as the α and β samples, α being the one nearer the base line of the acre. Duplicated samples are necessary to give a full statistical check on reliability of result.

(*b*) For the counts before singling the sample length should be 1 ft. (α and β both = 1 ft.).

(*c*) For all counts after singling and for weighing, the sample length should be 4 ft. (α and β both = 4 ft.).

(*d*) One end of every α sample will be determined as explained in § VI. Mark it by a peg between the pair of plants nearest to the determined point. If a plant happens to be exactly at the other end of the measured length, insert the second peg just inside or just outside this plant choosing the position to make the sample length as near to the exact stipulation as possible.

§ VIII. *Recording of results.*

For all counts and weighings on the acre results should be entered on copies of Diagram 1 (simplified copies as in the specimen Record Sheet on p. 597). The nature and date of the count should be fully shown. A specimen entry has been made on the Record Sheet (p. 597) showing α and β values at the point *D* 23.

SPECIMEN RECORD SHEET

Count of. ....

Date ....

Recorder's name ....

ROW / TRAVERSE	1	5	10	14	19	23	28	32	36	40	43	47	50	54	57	61	TOTAL
A																	
B																	
C																	
D						315											
E																	
F																	
G																	
H																	
J																	
K																	
L																	
M																	
N																	
TOTAL																	

§ IX. *Singling.*

A point of great importance is the closeness with which men on piece work adhere to the stipulated 10-in. interval between plants. As a test the acre should be singled by two, three, or four men, a very careful record being made of the rows they actually single (they will have to be supervised so that the rows done by each man may be known with certainty).

§ X. *Miscellaneous.*

(*a*) At harvest the roots from every sample length should be lifted, counted, and placed in a labelled bag. The bags can be removed under cover where weighing, etc. can be completed.

(*b*) For the bags in turn, "top" the roots, wash them with a brush or a sprayer, shake off excess water and weigh. The top need not be weighed unless it is desired to extend the experiment to tops. After weighing, return the roots to the bag for the sorting explained below. For weighing, a spring balance with a removable pan at the top will be convenient: the bag need not then be weighed.

(*c*) Weighing should be to the nearest *whole* pound only.

(*d*) Army sandbags or old sugar bags from the factory are convenient. Labels with metal clip should be used. Before lifting begins, write the numbers of the samples upon the labels and attach these to the bags. This will avoid both error and trouble in harvesting the samples. Use a hard pencil, write clearly, and press hard, so that the entries do not become effaced.

(*e*) It will be convenient to record all harvest data on the labels, afterwards copying out on to standard record sheets. Entries should be in order on the label thus:

(No. of sample)	*D* 23
(No. of roots)	4
(Wt of roots)	6 lb.

(*f*) Bolters should be included in the number of plants per sample and, in addition, the number of bolters should be shown in brackets after the total number of plants, *e.g.* 4 (1), *i.e.* 4 plants in the sample of which 1 was a bolter.

(*g*) For sugar determinations the samples should be sorted in five approximately equal groups and an analysis sample drawn from every group. Local arrangements will have to be made for analysis.

To decide on the grouping the number of samples having one plant, two plants, ... must be counted. If the one plant, two plant and three

plant samples total to about forty in all (one-fifth of the two hundred samples) they will constitute the first group and so on. It will not be possible to arrange the samples in five exactly equal groups: the nearest arrangement to this must be adopted.

(*h*) It is of great importance that *all* records of *every* kind be on paper of the same size.

§ XI. *An additional investigation.*

Agricultural stations grow beet crops well above the average of their localities. This they do largely by care in securing a full and even plant. On such crops irregularity of plant is probably not of great importance whereas on the average farmer's crop it does much to limit yield. Consequently the value of this investigation might be much enhanced by extending study to one or two farmers' crops. Average or below average fields should be selected. The full number of counts is not absolutely essential and the following would be a suitable scope:

(*a*) One count before singling.
(*b*) One count after the last horse hoeing.
(*c*) A count at harvest.
(*d*) If possible, weighings at harvest (as for the experiment proper).
(*e*) Periodic agricultural and growth notes.

§ XII. *Record sheets* (specimen on p. 597).

Sheets exactly similar to the specimen should be used for every count.

The alternate squares in every row across the table will be left blank as there are no samples corresponding to them, *e.g.* *A* 5, *A* 14, *A* 23, ...

Entries for the duplicate sample at any point go into the same square (see specimen entry on specimen form which implies that for sample *D* 23 there were five plants in the α sample and three in the adjoining β sample).

The row totals and column totals should be added up (α and β totals being separately shown) as soon as a count is made to see if the results across the table check with those down the table.

Attached to each record should be a "frequency distribution" of the results on that record. It should show, for α and β samples separately, the grouping of the samples in order of magnitude. Thus for a plant count

No. of plants per sample	No. of such samples
0	1
1	3
2	6
3	17

and so on.

*Key showing the Coulters by which the Sample Lengths were sown**.

Traverse	Row number and coulter number†							
A	1 (1)	10 (2)	19 (3)	28 (4)	36 (4)	43 (3)	50 (2)	57 (1)
B	5 (4)	14 (3)	23 (2)	32 (1)	40 (1)	47 (2)	54 (3)	61 (4)
C	1 (1)	10 (2)	19 (3)	28 (4)	36 (4)	43 (3)	50 (2)	57 (1)
D	5 (4)	14 (3)	23 (2)	32 (1)	40 (1)	47 (2)	54 (3)	61 (4)
E	1 (1)	10 (2)	19 (3)	28 (4)	36 (4)	43 (3)	50 (2)	57 (1)
F	5 (4)	14 (3)	23 (2)	32 (1)	40 (1)	47 (2)	54 (3)	61 (4)
G	1 (1)	10 (2)	19 (3)	28 (4)	36 (4)	43 (3)	50 (2)	57 (1)
H	5 (4)	14 (3)	23 (2)	32 (1)	40 (1)	47 (2)	54 (3)	61 (4)
J	1 (1)	10 (2)	19 (3)	28 (4)	36 (4)	43 (3)	50 (2)	57 (1)
K	5 (4)	14 (3)	23 (2)	32 (1)	40 (1)	47 (2)	54 (3)	61 (4)
L	1 (1)	10 (2)	19 (3)	28 (4)	36 (4)	43 (3)	50 (2)	57 (1)
M	5 (4)	14 (3)	23 (2)	32 (1)	40 (1)	47 (2)	54 (3)	61 (4)
N	1 (1)	10 (2)	19 (3)	28 (4)	36 (4)	43 (3)	50 (2)	57 (1)

* This applies to a four-coulter drill, the coulters being numbered 1 to 4 from left to right of a man walking behind the drill.

† In the key the first number is the number of the row; the second (in brackets) is the number of the coulter by which the row was sown.

APPENDIX II.

On Reliability of Result.

There are three essential results to consider. The first is the irregularity from foot to foot of the seedling population (Table II); next are the acre-mean-values (Table IV); finally the frequencies of population density gradations and the attributes associated with them (Table V). As explained in § II the one hundred sample points on the acre were selected to fall equally on the work of all four drill coulters. At every sample point a pair of adjacent samples, α and β, was drawn. Agreement between the α and β series in form and in mean values offers a general test of reliability of result. For this to be valid there must be no correlation between α and β values, *i.e.* they must be independent. Calculation shows that $\gamma_{\alpha\beta}$, the correlation between an α series of values and the corresponding β series, is non-significant for seedling population, populations after singling and at lifting, and yields of beet and of top at maturity. Agreement between the α and β series is therefore a test of reliability of result. The distributions of Tables II and V for α and β series are similar in form in that the order of magnitude of the class frequencies is identical. It remains to consider agreement between mean values of the series. In no attribute is $M_\alpha \sim M_\beta$ significant as judged by $\epsilon_{\alpha\beta}$ (standard error of difference between the means of two series of independent values).

BIBLIOGRAPHY.

(1) ENGLEDOW, F. L. (1926). A Census of an Acre of Corn (by sampling). *J. Agric. Sci.* **16.**

(2) (1926). A Census of an Acre of Barley. *J. Roy. Agric. Soc.* **87.**

(3) HUNTER SMITH, J. and WILLIAMS, RHYS H. (Aug. 1927). A Census of an Acre of Roots. *J. Min. Agric.* **34.**

(4) ENGLEDOW, F. L. (1928). Investigations on Yield in the Cereals. IV. The Action of the Seed Drill. *J. Agric. Sci.* **18.**

(5) DOUGHTY, L. R. and ENGLEDOW, F. L. (1928). Investigations on Yield in the Cereals. V. A Study of Four Wheat Fields: the Limiting Effect of Population-density on Yield and an Analytical Comparison of Yields. *J. Agric. Sci.* **18.**

(*Received June 1st*, 1928.)

STUDIES IN CROP VARIATION.

V. THE RELATION BETWEEN YIELD AND SOIL NUTRIENTS

By BH. BALMUKAND, M.A., M.Sc.

(*Rothamsted Experimental Station, Harpenden.*)

CONTENTS.

1. Introduction.

In spite of the manifest progress of plant physiology a deductive theory of the relation between the size of a plant and the environmental factors seems still remote. Our present knowledge is too small and scattered to serve as a basis for the formulation of any rigid laws. The only procedure open therefore to quantitative research is to attempt to establish empirically some relationship between yield and external factors; it may thereafter be possible to discover its physiological significance, and in any case to put it to practical use.

Liebig made an early attempt to formulate a relationship between the plant-yield and the intensity of the external factors. He stated that of all the factors there was one which was "in minimum" and that the size of the crop was determined by, and increased with, increase in this factor until a point was reached at which some other factor was in minimum. Mitscherlich and many other workers have, however, shown conclusively that the simple formula of Liebig is not a true expression of the yield-factor relationship. The law of plant-yield formulated by Mitscherlich (1), his expression for the relation between the yield and the environmental factors and the practical use and physiological significance of this expression, have all been very severely criticised by

Briggs(2). Throughout his work Mitscherlich stresses his idea that the value of the constant c in his expression

$$y = A(1 - e^{-cx}),$$

expressing the yield y in terms of the quantity of nutrient x, is dependent upon the nature of the factor and upon that alone, and yet it is precisely the change in the relation of growth to the single factor brought about by the interaction of other factors that needs to be known. In fact Briggs has successfully shown from Mitscherlich's own data that where only one factor, such as potassium, is varied at a time the relation between yield and factor is different for different values of the other nutrient—magnesium. In most cases where manure is added in the form of a salt, the factors increase simultaneously. When two factors with different constants are increased simultaneously the value of dy/dx is no longer given by the simple relation $dy/dx = c(A - y)$, and is thus no longer proportional to the deficit from the maximum. The relations worked out for two factors by Briggs show that if in investigating the effect of a single substance, such as potassium, a salt such as phosphate or nitrate is added, the conditions should be such that sufficient of the elements introduced as part of the salt (phosphate or nitrogen) is already present to render the effect of further increase of these elements negligible. More detailed data is surely required to decide the point raised by Mitscherlich that the constants for nitrogen are the same in the form of ammonium, urea and nitrate ions. Mitscherlich's work has paved the way for further thorough investigation, but his results bring out only two tangible facts, (i) that yield will be increased by an increase in any of the factors, provided c is positive, and (ii) that the value of dy/dx is proportional to the corresponding factor c and to the deficit of the yield at that point from the maximum attained when that particular factor is increased indefinitely. The hypothesis that "as far as variations in one factor alone are concerned the yield expressed as a fraction of the maximum yield obtained when that factor is very great is the same whatever may be the plant, portion of plant, time of harvest, and other growth conditions in weather, soil, etc." is not only open to challenge but entirely belied by agricultural as well as pot-culture data (see section 2). Mitscherlich has attempted to use his equation in conjunction with the results of pot-culture experiments to determine (a) the amount of a manurial substance in a sample of soil, and (b) the effect of the addition of artificial manure to field plots. In this practical use of the equation he does not employ any well recognised statistical method, and

with the adaptability of A and b allowed by him it is not surprising that values for the constants are found so that the values of y calculated on their basis give an agreement with observation which Mitscherlich considers satisfactory, although the main justification brought forward by him for his results is the agreement of the observed and the calculated values. Mitscherlich makes no attempt to measure statistically the precision of values obtained for his constants. In the absence of their standard errors it is difficult to judge the goodness of fit of these values, and their practical applications also become a matter of great doubt. All the evidence considered by Mitscherlich is based upon pot cultures and he himself seems to be in great difficulty to apply it in a suitable manner to field conditions.

2. Statement of the Problem.

Briggs has clearly shown that even in approaching the subject from Mitscherlich's direction we are not limited to his narrow path. From our knowledge of plants it is unlikely that when the conditions are made more and more favourable the size of a plant can go on increasing without limit. There are various possible yield-factor relations. The law of diminishing returns may hold throughout the whole range; the yield may increase proportionately with increased quantity of manure up to a certain point and then no further as Liebig suggested, although not independently of the interaction of other factors (a fact which was lost sight of by him); the return per outlay may increase with increase in outlay up to a certain point and then no further increase in the return will result; or we may have various combinations of these relations, but beyond a maximum return we cannot go. In the case of the plant and variation in one factor of the environment the law of diminishing returns seems to apply. The Mitscherlich one-factor equation is not the only equation which approaches a maximum value with ever decreasing return per outlay as outlay is increased. In fact Briggs has shown that some other equations fit even Mitscherlich's data much more closely than his particular equation. More recently Lemmerman (3) has come to the same conclusion. However, it is necessary to the understanding of the problem to examine the more general implications of Mitscherlich's yield equation $y = A(1 - e^{-cx})$. If the intensity of the factor changes to x', the value of the yield y' will equal the value $A(1 - e^{-cx'})$, or the change of y to y' will take place in the ratio $(1 - e^{-cx}) : (1 - e^{-cx'})$, *i.e.* independently of the value of A. All other factors governing the yield, besides the one under consideration, can affect the yield only by pro-

ducing some change in the value of A; this ratio, being independent of A, is therefore required to be uninfluenced by the condition of other factors at the time of the change. That such ratios are not in fact independent of the interaction of other factors can be shown from any fairly accurate agricultural data. The well-known data on wheat-yield from Broadbalk (4) supply a very clear case; the addition of a certain dose of nitrogen raises the yield in the ratio 1·589 : 1 (plots 3, 4 and 10) when no other salts are added, but the same dose of nitrogen in the presence of mineral salts is capable of raising the yield in the ratio 2·212 : 1 (plots 5 and 7).

Table I (A). *Broadbalk data. Manure per acre, in lb.*

Plot	Sulphate of potash	Sulphate of soda	Sulphate of magnesia	Superphosphate	Sulphate of ammonia	Chloride of ammonia	Mean bushels per acre	$\frac{y'}{y}$	$\frac{1}{y}-\frac{1}{y'}$
3 and 4	—	—	—	—	—	—	y 12·269	1·589	·03021
10	—	—	—	—	200	200	y' 19·504		
5	200	100	100	392	—	—	y 14·180	2·212	·03765
7	200	100	100	392	200	200	y' 31·367		

The same fact is clearly borne out by the yields of barley taken from the pot-culture investigations of Dr Gregory at Rothamsted regarding the interaction of nitrogen and phosphorus. Here the ratio of the yield obtained when 1215 mg. of nitrogen per pot are supplied to that when only 15 mg. are given, varies from 4·902 to 24·000 as the amount of phosphorus added rises from 5 to 405 mg. per pot.

Table I (B). *Pot-culture data.*

P_2O_5	Mg. of nitrogen per pot: 15	1215	Ratio of yields	Reciprocal difference
5	3·06	15·00	4·902	·2602
15	3·36	17·88	5·321	·2417
45	3·03	29·60	9·769	·2963
135	2·39	68·10	20·089	·2784
405	3·60	86·40	24·000	·2663

Mitscherlich's yield-factor relation fits neither the agricultural nor the pot-culture data, and it therefore fails to meet a requirement of yield formulae, which has been far too little appreciated. Not only must the formula represent satisfactorily the response to variations of a single factor, but also the response to simultaneous variations of two or more different factors. A yield-factor relation suggested by Maskell is critically tested in this paper and seems to fulfil this necessity. This, which by electrical analogy may be termed the Resistance Formula, requires that, instead of the ratio y'/y being independent of the influence of other factors,

when the value of one factor changes in intensity, $\frac{1}{y} - \frac{1}{y'}$, the difference of reciprocals of yields, should behave as such; the agreement of the several values of this difference both in the case of the field data and in that of the pot-culture data suggests that we have here at least a good approximation.

The succeeding sections are devoted to testing, by comparison with the best available data, formulae of the general resistance type, *i.e.*

$$\frac{1}{y} = F(N) + F'(K) + F''(P) + \dots + C,$$

and the derived Special Formulae in which F, F', F'' ... are inversely proportional to the nutrients available.

The purpose of this paper is therefore to show:

(*a*) By a method of approximation, detailed hereinafter, the satisfactory fit of the Resistance Formula to several sets of data.

(*b*) That the expressions $F(N)$ and $F'(K)$, etc. are well represented by the forms $\frac{a_n}{n+N}$ and $\frac{a_k}{k+K}$, etc., where N and K, etc. are the nutrients added to the soil and n, k, etc. those originally present in the soil, while a_n, a_k, etc. are the constants for the several types of manure added.

(*c*) That the harvesting data, when fairly freed of experimental errors by the method of approximation shown in section 3 (*a*), can be used for evaluating the terms a_n, a_k, n and k, and that these parameters obtained satisfactorily fit the experimental data.

(*d*) That the values of n and k obtained through this channel give us a new measure of soil fertility, which differs from the absolute quantity of plant food present in the soil in that it is rather the measure of the effect of the plant food in the soil in terms of the soil fertiliser. This new measure of soil fertility affords direct and independent evidence necessary to test the validity of laboratory methods for estimating the amount of the several nutrients in the soil. These values should also enable us to measure the immediate availability of plant food in different manures and their residual value for the succeeding crops.

(*e*) That the standard errors of the values of the several terms obtained can be measured. This is necessary to obtain trustworthy conclusions free from any subjective bias. These are also required in the design of agricultural experiments capable of yielding more precise and accurate results.

(*f*) That these values of the constants when obtained with sufficient accuracy should enable us to answer such problems as the "optimum value for a given manure" or a balanced manure for two or more kinds of nutrients with great confidence.

3. Material and Methods of Investigation.

(*a*) *General Resistance Formula.*

The choice of material for the development of the method was due solely to circumstances. The absence of any very accurate data seems to stand for the present in the way of the investigations being pushed much farther beyond the present stage. The writer is, however, of opinion that not only is the method employed essentially applicable to field trials and pot cultures, but that it could be applied to any type of plant-yield data by introducing suitable modifications in the system of weighting, etc. The following example is chosen to illustrate the process of fitting and testing the Resistance Formula.

Table II. *Potatoes (Kerr's Pink), Stackyard Field, Rothamsted,* 1926. *Average yield in tons per acre (y).*

		Cwt. per acre, sulphate of potash			
		0	1	2	4
Cwt. per acre, sulphate of ammonia	0	7·80	7·80	8·01	7·79
	1	7·73	8·98	9·17	9·01
	2	9·40	10·56	10·30	10·44
	4	9·53	11·15	11·62	12·34

System of replication: Randomised blocks for all manurial combinations. Plots 1/50 acre. Basal dressing 3 cwt. superphosphate per acre.

Approximation. As already stated the central idea in the Resistance Formula, is that the reciprocal of the yield $\left(\frac{1}{y}\right)$ is the sum of several portions, each a function of one nutrient, like $F(N)$, $F'(K)$, etc., and that fact is here utilised in building up a series of expectations of yield. The measure of agreement of the expected yields with the observed yields would thus afford us a means to judge the accuracy of our hypothesis.

It is first necessary to obtain crude values of the expected yields, that is, values obeying the Resistance Formula and approximate to those observed. The fourth powers of these crude expectations may then be used as weights in obtaining the improved fit.

Table III. *Reciprocals of the yield* $\left(\frac{1}{y} \text{ or } x\right)$.

					Means of rows (a)
	·1282	·1282	·1248	·1284	·1274
	·1294	·1114	·1090	·1110	·1152
	·1064	·09470	·09709	·09579	·09848
	·1049	·08969	·08606	·08104	·09042
Means of columns (b)	·1172	·1060	·1042	·1041	·1079 (c)

Table IV (A). *Reciprocals of expected yields* $\left(\frac{1}{m}\right)$ *built from the margins of Table III by the summation formula* $a + b - c$.

·1367	·1255	·1237	·1236
·1245	·1133	·1115	·1114
·1078	·09659	·09479	·09469
·09972	·08852	·08672	·08662

Table IV (B). *Values of* m.

7·315	7·968	8·084	8·091
8·032	8·826	8·969	8·977
9·276	10·353	10·550	10·561
10·028	11·297	11·531	11·545

$$\Sigma (y - m)^2 = 1{\cdot}5331.$$

Table IV (C). *Values of* m^4.

					Sums of rows
	2,863	4,031	4,271	4,286	15,451
	4,162	6,068	6,471	6,494	23,195
	7,404	11,489	12,388	12,440	43,721
	10,112	16,287	17,679	17,761	61,839
Sums of columns	24,541	37,875	40,809	40,981	144,206

The margins in the next table (Table V) are built up by taking the weighted averages of the reciprocals in Table III row by row and column by column. The weights are taken equal to the corresponding values of m^4, these being inversely proportional to the variances of the reciprocals in field trials, where the variance in yield is usually independent of yield. This set of weights makes the residual variance approximately a minimum. In the example from pot cultures (see Appendix II) where the variance increases with the value of the yield, the total variance becomes least when the weights are taken equal to the corresponding values of m^2. The value ·09958 (Table V) is the weighted average of the 16 entries of Table III, and it provides a useful arithmetical check to obtain it from each set of marginal means in turn. This value ·09958 has been subtracted

from the row margins to facilitate the arithmetic. The several values of $\left(\frac{1}{m}\right)$ in Table V are then obtained by adding the marginal values p_s and q_t.

Table V. *Reciprocals of expectations* $\left(\frac{1}{m}\right)$.

					q_t
·13993	·12652	·12483	·12295	·12731	·02773
·12646	·11305	·11136	·10948	·11384	·01426
·11029	·09688	·09519	·09331	·09767	–·00191
·10127	·08786	·08617	·08429	·08865	–·01093
·11200	·09879	·09710	·09522	·09958	

The values of m are calculated and thence the sum of the squares of the residuals $\Sigma\,(y-m)^2$ which is found to be 1·294. The drop in the value of $\Sigma\,(y-m)^2$ from the previous figure 1·5331 to 1·294 shows that the fit of the expected yields (m) to the observed values (y) has considerably improved by this process of weighting.

The approximate values of the margins p_s and q_t are then improved with a view to making the sum of products of the weights and expectations equal to the sum of products of the weights and the actual yields along rows and columns. The several corrections required are calculated as follows:

Let $a_{11}, a_{12}, a_{21}, a_{22} \ldots a_{44}$ be the true reciprocals of expectations, $x_{11}, x_{12}, x_{21}, x_{22} \ldots x_{44}$ the reciprocals of the observed yields, and

$$w_{11},\ w_{12},\ w_{21},w_{22}\ \ldots\ x_{44}$$

the weights as used above; then

$$w_{11}a_{11}+w_{12}a_{12}+w_{13}a_{13}+w_{14}a_{14}=w_{11}x_{11}+w_{12}x_{12}+w_{13}x_{13}+w_{14}x_{14}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$w_{41}a_{41}+w_{42}a_{42}+w_{43}a_{43}+w_{44}a_{44}=w_{41}x_{41}+w_{42}x_{42}+w_{43}x_{43}+w_{44}x_{44}$$

along columns,

and $$w_{11}a_{11}+w_{21}a_{21}+w_{31}a_{31}+w_{41}a_{41}=w_{11}x_{11}+w_{21}x_{21}+w_{31}x_{31}+w_{41}x_{41}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$

$$w_{14}a_{14}+w_{24}a_{24}+w_{34}a_{34}+w_{44}a_{44}=w_{14}x_{14}+w_{24}x_{24}+w_{34}x_{34}+w_{44}x_{44}$$

along rows.

Suppose $a_{st}=p_s+q_t$ where p_s and q_t represent true marginal values; then by substitution we get the equations:

$$(w_{11}+w_{12}+w_{13}+w_{14})\,p_1+w_{11}q_1+w_{12}q_2+w_{13}q_3+w_{14}q_4$$
$$=S\,(w_{1t}x_{1t}),\ \text{etc. along columns (4 equations)}\quad\ldots\ldots(\mathrm{I}),$$

and similarly

$$(w_{11}+w_{21}+w_{31}+w_{41})\,q_1+w_{11}p_1+w_{21}p_2+w_{31}p_3+w_{41}p_4$$
$$=S\,(w_{s1}x_{s1}),\ \text{etc. along rows (4 equations)}\quad\ldots\ldots(\mathrm{II}),$$

or $$p_1 = \frac{S(w_{1t}x_{1t})}{S(w_{1t})} - \frac{S(w_{1t}q_t)}{S(w_{1t})} \quad \text{......(equations I)},$$

and $$q_1 = \frac{S(w_{s1}x_{s1})}{S(w_{s1})} - \frac{S(w_{s1}p_s)}{S(w_{s1})} \quad \text{......(equations II)}.$$

By inserting in equations (I) the values of q in the last table, we obtain a new series of p. Then from this new series of p we re-calculate the values of q by equations II.

The corrected values of p and q are now used to build a new table (VI) of reciprocals of expectations:

Table VI. *Table of reciprocals of expectations* $\left(\frac{1}{m}\right)$.

				q_t
·13913	·12633	·12475	·12287	·02750
·12575	·11295	·11137	·10949	·01412
·10973	·09693	·09535	·09347	−·00190
·10080	·08800	·08642	·08454	−·01083
·11163	·09883	·09725	·09537	

A table of weighted discrepancies between the observed and the expected values is then prepared by multiplying the differences $\left(\frac{1}{y} - \frac{1}{m}\right)$ by the weights used above. If the discrepancies are well distributed, the marginal totals ought to be very small compared to the individual values in the corresponding rows or columns as in Table VII. If however it is not so, the margins are further corrected as shown below and a similar table again calculated, when the condition for the fair distribution of discrepancies will be found to be more nearly fulfilled.

Table VII. *Weighted discrepancies between reciprocals of observed and expected values of yield.*

−31·293	+ 7·538	+ 0·214	+23·702	+ ·161
+15·191	− 9·405	−15·336	+ 9·806	+ ·256
−24·655	−25·620	+21·555	+28·861	+ ·141
+41·459	+27·525	− 6·364	−62·164	+ ·456
+ 0·702	+ 0·038	+ 0·069	+ 0·205	1·014

Suppose e_1, e_2, e_3, e_4 and f_1, f_2, f_3, f_4 are the corrections required in the values of p and q as determined from equations (I) and (II) in order to bring them as near the true expectations as possible. Then equations (I) can be written as

$$(w_{11} + w_{12} + w_{13} + w_{14})(p_1 + e_1) + w_{11}(q_1 + f_1) + w_{12}(q_2 + f_2) + w_{13}(q_3 + f_3) + w_{14}(q_4 + f_4) = S(w_{1t}x_{1t}) - \cdot 702,$$

or $$S(w_{1t}).e_1 + w_{11}f_1 + w_{12}f_2 + w_{13}f_3 + w_{14}f_4 = -\cdot 702.$$

Assuming the set of margins q_t to be correct, the values of f are taken to be zero, and in that case

$$e_1 = \frac{-\cdot 702}{S\,(w_{1t})} \text{ and so on.}$$

Similarly the equations (II) give

$$S\,(w_{s1})\,.f_1 + w_{11}e_1 + w_{21}e_2 + w_{31}e_3 + w_{41}e_4 = -\cdot 161, \text{ etc.},$$

and the values of f are calculated from the values of e now determined. The values of the quantities e and f for the case in hand were found to be as follows:

e_1	·00003	f_1	0
e_2	0	f_2	0
e_3	0	f_3	0
e_4	·00001	f_4	0.

Applying these corrections, the new values for p and q (now denoted by p_t and q_t) were obtained and therefrom tables for the reciprocals of expectations, the expectations and the weighted discrepancies between the observations and the expectations were calculated.

Table VIII (A). *Reciprocals of expectations* $\left(\frac{1}{m}\right)$.

					q_t
	·13916	·12633	·12475	·12288	·02750
	·12578	·11295	·11137	·10950	·01412
	·10976	·09633	·09535	·09348	−·00190
	·10083	·08800	·08642	·08455	−·01083
p_t	·11166	·09883	·09725	·09538	

Table VIII (B). *Expectations* (m).

7·184	7·918	8·013	8·137
7·949	8·850	8·977	9·132
9·107	10·317	10·488	10·697
9·921	11·364	11·571	11·827

$\Sigma\,(y-m)^2 = 1\cdot 341.$

Table VIII (C). *Weighted discrepancies* $\left[w\left(\frac{1}{y}-\frac{1}{m}\right)\right]$.

−31·378	+ 7·538	+ ·214	+23·659	+·033
+15·066	− 9·405	−15·336	+ 9·741	+·066
−24·877	−25·620	+21·555	+28·736	−·206
+41·156	+27·525	− 6·364	−62·341	−·024
− ·033	+ ·038	+ ·069	− ·205	−·131

In case the marginal values of the weighted discrepancies in Table VIII (C) are still found to be large, the fourth powers of the values of m in Table VIII (B) are taken as improved weights and the whole process repeated. This was found necessary in the case of the pot-culture data.

(b) *Special Resistance Formula.*

It has been shown in the previous section that the reciprocal of the yield $\frac{1}{y}$ can be built up by adding the two expressions $F(N)$ and $F'(K)$. This section deals with the investigation of the approximate forms of these expressions. It appears from the analysis made in the succeeding pages that $F(N)$ and $F'(K)$ are within a sufficient degree of accuracy of the forms $\frac{a_n}{n+N}$ and $\frac{a_k}{k+K}$. a_n and a_k vary with the nutrient and the crop and are therefore called importance factors: for they measure the importance of the particular nutrient to the crop manured. Possibly they would vary to some extent with the nature of the soil and weather conditions, but such variations are not evident in the data used for the present paper. k and n represent the available potash and nitrogen in the unmanured soil in terms of cwt. of sulphate of potash and sulphate of ammonia per acre. The values for these constants were determined as shown below.

From special Resistance Formula:

$$p_1 = c + \frac{a_k}{k+K_1} \text{ and } p_4 = c + \frac{a_k}{k+K_4},$$

$$\therefore p_1 - p_4 = a_k \frac{K_4 - K_1}{(k+K_1)(k+K_4)} \text{ or } \frac{K_4 - K_1}{(p_1 - p_4)} = (k+K_1)\frac{k+K_4}{a_k} \quad \text{......(III)},$$

and from the values of p_t given in Table VIII (A) we get:

Table VIII (D)

Manure (K_t) added in cwt. per acre	1 Total manure ($k+K_t$)	2 p_t	3 $p_t - p_4$	4 $\frac{K_4 - K_t}{p_t - p_4}$
0	$K+0$	·11166	·01628	245·7
1	$K+1$	·09883	·00345	869·6
2	$K+2$	·09725	·00187	1069·5
4	$K+4$	·09538		

We expect from the reasoning given in equation (III) that the values given in columns 1 and 4 of the above table when plotted ought to give a straight line graph. The point where this line cuts the x-axis gives us roughly a measure of k, the potash manure available in the unmanured soil. The value of k is found to be equivalent to an added manure of 0·8 cwt. of sulphate of potash per acre. From this approximate value of k the value of a_k was calculated to be ·0156. These values of k and

a_k were used to prepare the next table (VIII (E)), the value of c in each case being obtained by subtracting the values in column 3 from those in column 2.

Table VIII (E).

1	2	3	4	5	6
$k+K_t$	p_t	$\frac{a_k}{k+K_t}$	c	$c+\frac{a_k}{k+K_t}$ ($c = \cdot 09100$ approximately)	$c+\frac{a_k}{k+K_t}-p_t=\partial_t$
·8	·11166	·01950	·09216	·11050	−·00116
1·8	·09883	·00866	·09017	·09966	+·00083
2·8	·09725	·00557	·09168	·09657	−·00068
4·8	·09538	·00411	·09127	·09511	−·00027

Assuming the approximate value of c to be ·09100, the values in column 5 were obtained by adding this value to the corresponding values of $\frac{a_k}{k+K_t}$ in column 3.

The next problem is to fit the values in column 5 to the corresponding values obtained from the General Formula and given in column 2. The necessary corrections in the values of the quantities c, a_k and k for the purposes of best fit were calculated by the method of least squares as follows:

Let $Q = \underset{t=1}{\overset{4}{S}} \left\{ w_t \left(c + \frac{a_k}{k+K_t} - p_t \right)^2 \right\}$ be the expression to be minimised, and a_k, k and c be an approximate solution; then the next approximation $a + a''$, $k + k''$, $c + c''$ will be given by the equations

$$0 = \frac{\partial Q}{\partial (a_k + a'')} = \frac{\partial Q}{\partial a_k} + a'' \frac{\partial^2 Q}{\partial a_k^2} + k'' \frac{\partial^2 Q}{\partial a_k \partial k} + c'' \frac{\partial^2 Q}{\partial a_k \partial c},$$

$$0 = \frac{\partial Q}{\partial (k + k'')} = \frac{\partial Q}{\partial k} + a'' \frac{\partial^2 Q}{\partial a_k \partial k} + k'' \frac{\partial^2 Q}{\partial k^2} + c'' \frac{\partial^2 Q}{\partial k \partial c},$$

$$0 = \frac{\partial Q}{\partial (c + c'')} = \frac{\partial Q}{\partial c} + a'' \frac{\partial^2 Q}{\partial a_k \partial c} + k'' \frac{\partial^2 Q}{\partial k \partial c} + c'' \frac{\partial^2 Q}{\partial c^2},$$

where

$$\frac{\partial Q}{\partial a_k} = \underset{t=1}{\overset{4}{S}} \frac{2w_t}{k+K_t} \left(c + \frac{a_k}{k+K_t} - p_t \right), \quad \frac{\partial^2 Q}{\partial a_k^2} = \underset{t=1}{\overset{4}{S}} \frac{2w_t}{(k+K_t)^2},$$

$$\frac{\partial Q}{\partial k} = - \underset{t=1}{\overset{4}{S}} \frac{2w_t a_k}{(k+K_t)^2} \left(c + \frac{a_k}{k+K_t} - p_t \right),$$

$$\frac{\partial^2 Q}{\partial k^2} = \underset{t=1}{\overset{4}{S}} \left\{ \frac{2w_t a_k^2}{(k+K_t)^4} + \frac{w_t a_k}{(k+K_t)^3} \left(c + \frac{a_k}{k+K_t} - p \right) \right\},$$

$$\frac{\partial Q}{\partial c} = \overset{4}{\underset{t=1}{S}} 2w_t \left(c + \frac{a_k}{k + K_t} - p_t\right), \quad \frac{\partial^2 Q}{\partial c^2} = \overset{4}{\underset{t=1}{S}} (2w_t),$$

$$\frac{\partial^2 Q}{\partial a_k \partial k} = -\overset{4}{\underset{t=1}{S}} \frac{2w_t a_k}{(k + K_t)^3} + \frac{2w_t}{(k + K_t)^2}\left(c + \frac{a_k}{k + K_t} - p_t\right),$$

$$\frac{\partial^2 Q}{\partial a_k \partial c} = \overset{4}{\underset{t=1}{S}} \frac{2w_t}{k + K_t} \text{ and } \frac{\partial^2 Q}{\partial c \partial k} = -\overset{4}{\underset{t=1}{S}} \frac{2w_t a}{(k + K_t)^2}.$$

The evaluation of the quantities $\frac{\partial Q}{\partial a_k}, \frac{\partial^2 Q}{\partial a_k^2}$ and $\frac{\partial^2 Q}{\partial a_k \partial k}$, etc. is facilitated by the preparation of a table like the following (VIII (F)):

Table VIII (F).

∂_t	w_t	$k+K_t$	$\frac{w_t}{k+K_t}$	$\frac{w_t}{(k+K_t)^2}$	$\frac{w_t}{(k+K_t)^3}$	$\frac{w_t}{(k+K_t)^4}$
−·00116	24,541	·8	30,676	38,345	47,931	59,913
+·00083	37,875	1·8	21,042	11,690	6,494	3,608
−·00068	40,809	2·8	14,575	5,205	1,859	664
−·00027	40,981	4·8	8,538	1,779	371	77
			74,831	57,019	56,655	64,262

The values of $\frac{\partial Q}{\partial a_k}, \frac{\partial^2 Q}{\partial a_k^2}, \frac{\partial^2 Q}{\partial a_k \partial_k}$, etc. are then substituted in the equations derived from minimising the sum of the squares of the differences and the equations solved for a'', k'' and c''. The corrections a'', k'' and c'' were found to be − ·0067, − ·32 and − ·00179 respectively. The corrected values of a_k, k and c therefore become ·0089, ·48 and ·09279, and these are used to calculate the new values of p, *i.e.* $c + \frac{a_k}{k + K_t}$ best fitted with the values of p obtained from the General Formula. By an exactly similar process the values of the quantities a_n, n and c' were determined from the values of q in Table VIII (A) and found to be ·0986, 1·7275 and − ·02771. The new values of q were then calculated from the relation $q_t = c' + \frac{a_n}{n + N_t}$. These values of p and q were then used for building up reciprocals of expectations obeying the implications underlying the special Resistance Formula. These expectations are given in Table IX.

Table IX (A). *Reciprocals of expectations from special Resistance Formula* $\left(\frac{1}{m}\right)$.

					q_t
	·14070	·12817	·12575	·12415	·02937
	·11977	·10724	·10482	·10322	·00844
	·11007	·09754	·09512	·09352	−·00126
	·10084	·08831	·08589	·08429	−·01049
p_t	·11133	·09880	·09638	·09478	

Table IX (B). *Expectations from special Resistance Formula* (*m*).

7·10	7·80	7·95	8·05
8·35	9·33	9·54	9·69
9·08	10·25	10·51	10·69
9·92	11·32	11·64	11·86

$$\Sigma (y - m)^2 = 2{\cdot}3832.$$

(c) *Other data examined.*

Two more sets of data on potato crops were next examined. These were made available by the courtesy of the authorities of the Seale-Hayne Agricultural College. These two crops were sown and raised under almost the same conditions with the only difference that in the case of one the plots were uniformly manured with 10 tons of dung per acre, whereas in the other crop the plots were left undunged. Otherwise in both cases four plots were devoted to each treatment as in the experiment on Stackyard Field discussed in section 3 (*a*), and the doses of the sulphate of ammonia and sulphate of potash were 0, 1, 2 and 3 cwt. per acre. A close examination of the values of constants determined from these two sets of data reveals many points of great interest. Whereas in the undunged plots the addition of the potash manure had a slightly depressing effect ($a_k = -{\cdot}0075$), if any, the addition of dung made the same soil in a position to profit nearly three times ($a_k = {\cdot}0258$) as much as in the case of Stackyard Field ($a_k = {\cdot}0089$). Similarly the importance of nitrogen to the crop when the Seale-Hayne soil was undunged ($a_n = {\cdot}0788$) was slightly less than that in the case of Stackyard Field, but with the dung added to the soil this importance of nitrogen ($a_n = {\cdot}168$) became nearly twice as much. The farmyard manure thus not only enriches the soil in the way of adding to it definite quantities of nitrogen and potash, but also changes the physical condition of the soil and makes it more susceptible to the advantages of adding further doses of artificial fertilisers. The differences between the values of *n* and those of *k* obtained from these two sets of data give us a measure of the nitrogen and potash made available to the plant by the addition of farmyard manure. This point is more fully dealt with in subsection (*e*).

Besides these sets of data in potato crops the yields of barley pot cultures grown by Dr Gregory at Rothamsted have been examined and the results embodied in Appendix II. This experiment was conducted to study the reaction of nitrogen and phosphatic manures. In the case of nitrogen 15, 45, 135, 405, 1215 mg. were added per pot, whereas in the case of P_2O_5 the doses were 5, 15, 45, 135, 405 mg. per pot. The whole arrangement resulted in 25 different treatments. The value of a_n is nearly eight times the value of a_p showing the comparatively much greater importance of nitrogen in increasing the yields. Although the sand used for growing the cultures is washed free of nitrogen it is found to have available to the plant nitrogenous food equivalent to 13·947 mg. of nitrogen added in the form of the fertiliser. The source of this nitrogen and its value have been critically examined in subsection (*e*). That the sand is found to contain available plant-food equivalent to 16·4 mg. of P_2O_5 does not require any explanation.

(*d*) *Tests of goodness of fit.*

It was shown in section 2 that the natural sequence of Mitscherlich's one-factor relation is to expect that the proportionate change in yield produced by varying the intensity of one factor is not influenced by the prevailing intensities of the other factors, and that this expectation is belied by both field experiments as well as pot cultures. Let us now examine the similar sequence of the Resistance Formula with a view to testing its agreement with the several data handled. The one-factor relation as obtained from the Resistance Formula is $\frac{1}{y} = c + \frac{a_n}{n+N}$. When the intensity of N changes to N', the corresponding yield y' is given by the relation $\frac{1}{y'} = c + \frac{a_n}{n+N'}$. The difference between the reciprocals of the two yields, *i.e.* $\frac{1}{y} - \frac{1}{y'}$ is independent of c or the influence of the other nutrients or prevailing conditions of the experiments. That this expectation is borne out by the experimental data will be seen from a perusal of the values of $\frac{1}{y} - \frac{1}{y'}$ obtained in Tables I (A) and (B). It can be easily shown that this relation leads us to expect that the yields will increase with the increase in the quantity of the manure applied and that this rate of increase of yield falls down as the intensity of the manurial application becomes greater and greater.

Fit of the General and Special Formulae.

The precise fit of these two formulae was however tested by the method of the analysis of variance as developed by Dr R. A. Fisher(5). In the Rothamsted potato data the general analysis for 16 treatments tested in quadruplicate in four randomised blocks gave:

Differences due to	Degrees of freedom	Sum of squares	Mean square	Standard error
Blocks	3	5·6307	1·8769	
Treatments	15	130·2778	8·6852	
Remainder	45	48·5053	1·0779	1·0382 tons
Total	63	184·4138		

(S.E. of means of four = 0·5191.)

The test of any formula consists in the further analysis of the 15 degrees of freedom due to treatments into two parts representing the portion expressible in the type of formula tested and the residuum not so expressible. If the fit is good and the deviation from the formula may be regarded as due solely to chance, the mean square of this residuum will not be significantly larger than that due to field error, as found above from the 45 degrees of freedom. The General Formula involves 6 degrees of freedom leaving 9 for deviations from the formula. Similarly in the Special Formula after filling the four constants, the deviations from the Special Formula account for the remaining 11 degrees of freedom. The mean squares due to the deviations from the General and the Special Formulae, when compared with the mean squares due to parallels, show that the yields obtained from either of these agree very closely with the observed yields. The sum of squares corresponding to the 9 and 11 degrees of freedom were obtained by multiplying by 4 the values of the expression $\Sigma\,(y - m)^2$ calculated from the yields as expected from the General and Special Formulae, since the yields we have been using so far are based upon the means of four plots each.

Analysis of Variance to show the residuum due to General and Special Formulae.

Differences due to	Degrees of freedom	Sum of squares		Mean square
Parallels	45	48·5053		1·078
General Formula	6	124·914	130·278	20·819
	9	5·364		·596
Special Formula	4	118·076	130·275	29·519
	11	12·199		1·109

It is evident that there is no significant deviation from either the General or the Special Formula.

Standard errors of the constants. The standard errors of the values of a_n, a_k, n and k were evaluated by the method of maximum likelihood (5) as developed in Appendix I, where it is shown that

$$V(a_k) = \sigma^2 \frac{\begin{vmatrix} \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^4} & -\overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^2} \\ -\overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^2} & \overset{4}{\underset{t=1}{S}} (w_t) \end{vmatrix}}{\begin{vmatrix} \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^2} & -\overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^3} & \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{k+K_t} \\ -\overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^3} & \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^4} & -\overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^2} \\ \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{k+K_t} & -\overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^2} & \overset{4}{\underset{t=1}{S}} w_t \end{vmatrix}}$$

and $$V(k) = \frac{\sigma^2}{a^2} \begin{vmatrix} \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{(k+K_t)^2} & \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{k+K_t} \\ \overset{4}{\underset{t=1}{S}} \dfrac{w_t}{k+K_t} & \overset{4}{\underset{t=1}{S}} w_t \end{vmatrix} \div D$$

(where D is the denominator of the previous fraction).

The calculation of the values of $V(a_k)$ and $V(k)$, and therefrom of $\sigma(a_k)$ and $\sigma(k)$, was much facilitated by preparing the following table:

w_t	$k+K_t$	$w_t/k+K_t$	$w_t/(k+K_t)^2$	$w_t/(k+K_t)^3$	$w_t/(k+K_t)^4$
24,541	·48	51,127	106,514	221,904	462,300
37,875	1·48	25,591	17,291	11,683	7,894
40,809	2·48	16,455	6,635	2,675	1,079
40,981	4·48	9,148	2,042	456	102
144,206		102,321	132,482	236,718	471,375

The values of $\sigma(a_k)$ and $\sigma(k)$ are found to be ·0129 and ·597, which are rather too big and point out the necessity of more accurate data to evaluate the quantities a_k and k. Similarly the values of $\sigma(a_n)$ and $\sigma(n)$ were found to be ·0616 and ·852 respectively.

(*e*) *Practical applications of the Resistance Formula.*

The yield curve obtained by the variation of one single factor can with more or less accuracy be represented by any number of algebraic relations, but all these suffer from the inherent weakness that the constants involved will only fit the particular experiment from which these have been evaluated. These constants are thus of no practical use since they cannot be applied to predict the yields in other experiments. Moreover no physical interpretation of these constants can be made. It

is here in its practical applications and the physical interpretation of the constants involved that the strength of the Resistance Formula lies.

The constants *n*, *k*, etc. measure the soil fertility in respect of nitrogen, potash, etc. in terms of these manures applied, *i.e.* in cwt. of sulphate of ammonia or potash applied per acre. They do not measure the quantity of plant food present in the soil but what is of more immediate use, viz. the quantity of plant food actually available in the soil for the use of the plant. The difference between the two values of *k* obtained from the two sets of data from Seale-Hayne (see Appendix II) comes out to be equivalent to nearly 1·2 cwt. of sulphate of potash per acre, which is equivalent to about 70 lb. of K_2O per acre. Now these two experiments were carried out on similar soil in the same year with the only difference that in the case of one experiment ten tons of dung per acre were added as farmyard manure, while the other field was unmanured. The potash added through ten tons of dung is equivalent to about 112 lb. of K_2O per acre (7), out of which 70 lb., or nearly 62 per cent., becomes available as plant food the very first year. In the case of nitrogen, however, out of 110 lb. added to every acre through ten tons of dung only 24 lb. became available as plant food in the first year. This difference in the behaviour of potash and nitrogen added to the soil in ten tons of farmyard manure agrees very well with some experiments conducted in Germany (8) on the recovery of potash and nitrogen in potatoes (78 per cent. and 36 per cent.). In the case of the more precise pot cultures (see Appendix II) the calculated values of *p* and *n* agree still more closely with the facts. From the analysis of the barley plant raised in the data referred to above it was estimated that when only 5 mg. of phosphoric anhydride were added to the pot about 26·1 mg. were recovered in the plant. This surplus of 21·1 mg. must have come from the unmanured sand and is sufficiently near the figure 16·4 mg. obtained by fitting the Resistance Formula to the yields as available phosphorus present in the sand before any manure was added to it, if we took into consideration that the standard error of *p* is about 3·2. Although the sand was washed free of nitrogen, during the course of the experiment a certain amount must have been added in the rain and the seed. For the months of March to August at Rothamsted the average nitrogen in the rain is about 2 lb. per acre which is 11 mg. to a 10-inch pot. The seed must supply very nearly 1 mg. each. Nine were sown but only three plants retained, the remaining six being in most cases at least eradicated. We may thus account for 11 mg. from rain and 3 mg. or a trifle more in the seed, against 13·95 mg. indicated by the Resistance Formula. This method of measuring the amount of any

nutrient available to the crop makes direct use only of the behaviour of the plant itself, whereas any laboratory method leaves a great deal of uncertainty as to the availability of the substances measured. It is believed that this method might prove to be of great value for the purposes of soil survey.

The other set of constants a_n, a_k, a_p, etc. seem to determine the importance of the manure to the crop or it may be the capacity of the crop to recover the particular manurial nutrient out of the soil. It is believed that these values depend upon the nature of the crop and the variety of the crop as well. Whether the nature or composition of the soil exerts any influence upon these constants cannot yet be investigated for want of suitable data. The values ·098, ·168 and ·079 cwt. of sulphate of ammonia per ton of potatoes obtained for a_n in all the three potato experiments seem to be quite as close to each other as the standard errors allow us to expect. They are also of the same order as the minimum nitrogen content of potatoes. Kellner gives nitrogen percentages down to 0·23, which is equivalent in our units to 1·20 lb. sulphate of ammonia per ton of potatoes under nitrogen starvation conditions. Similarly the value of a_n from the barley pot culture (8·204) is pretty close to the mg. of nitrogen recovered per gm. of barley crop shown by the analysis of crop (about 7) under nitrogen starvation conditions. A similar agreement is found in the case of a_p (1·13) with the amount of phosphorus expressed as P_2O per gm. dry weight in barley under phosphorus starvation conditions. The practical value of examining more fully the interpretation of these constants cannot be over-emphasised, for these would give us both the optimum value of a single nutrient for any crop as well as the "balanced manure" in case of two or more nutrients for a particular crop and soil. An examination of the manner in which the standard error depends on the design of the experiment would help us in designing more accurate experiments and would thus enable us to determine the constants with greater precision. This knowledge might help us to find the most suitable levels of manures to be used in any experiment and might also throw some light on the possibility of an increase in accuracy being obtained by increasing replications at one level at the cost of another level.

4. Summary and Conclusions.

The study of the relation of plant-growth to environmental factors has led to much research directed to the elaboration of General Formulae expressing the quantitative response of the experimental plant or crop

to the quantity of the nutrients with which it is supplied. For variations of a single nutrient only many different mathematical expressions will serve to describe the facts to the accuracy with which these are usually ascertained by experiment; the practical value of such formulae is, however, much impaired if the parameters or constants which they involve change their value from experiment to experiment. If, on the contrary, we can obtain formulae of a general character which represents satisfactorily not only the response to variation of a single factor, but the response to simultaneous variation of two or more different factors, then we have reason to believe that the parameters of such formulae will not depend upon the casual or non-essential conditions of the experiment, but will be capable of direct interpretation as physical quantities. We have shown that the Resistance Formula does fit the data of several two-factor experiments and the agreement of the three values of a_n determined from the three potato crops as well as the agreement of the difference in the values of k on a dunged and undunged plot with the potash expected to be available from the ten tons of dung shows that this expectation is so far justified. The parameters of the Resistance Formula are capable of a direct and definite physical interpretation; for each nutrient there are two constants; one represents the importance of the nutrient considered to the crop concerned, and may be expected to vary from crop to crop and from variety to variety, and so to afford a direct comparison between varieties of their manurial needs, while the second represents the amount of nutrient available in the unmanured soil. The practical importance of this second parameter is also very great, for no chemical determination can be relied upon to evaluate the available nutrients, whereas this method renders it possible to evaluate this quantity directly by means of field experiments.

It is shown (a) that it is possible to fit the Resistance Formulae described above to experimental data involving the simultaneous variation of two factors by a sufficiently rapid method of approximation; (b) that in every case discussed the formula fits the facts within the limits of experimental error estimated from the experiments themselves, although formulae of other types fail strikingly to do so. This fact is strikingly borne out from the analysis of variance worked out for the several sets of data; (c) that the parameters appropriate to each nutrient are therefore independent of the abundance of other nutrients and are capable of direct physical interpretation; (d) that even in the best experiments available the sampling errors are too large to allow of estimates of available nutrients to a desirable degree of accuracy, and that greater

precision is also to be desired in the importance factor. This will be possible not only by increased replication, but also with the same number of replicates by an adjustment of the amounts of manure employed as well as by unequal replication of plots with different amounts of manure depending upon the special requirements of the problem; (*e*) that these constants have great practical value in as much as a knowledge of these would enable us to determine the optimum value of a nutrient for any crop under a given set of conditions. The knowledge of these constants would also help us to recommend an economic and balanced manure containing two or more nutrients for a given crop and soil; (*f*) it is worth mentioning here that if for certain crops a_n could be taken as known from the composition of the crop (i) n could be determined with increased precision, (ii) would be determinate from single dose experiments, and (iii) it would be possible to try an improved type of special formulae, *i.e.*

$$F(N) = \frac{a_n}{n+N} - \frac{b_n}{(n+N)^2}.$$

It is not claimed, nor is it considered probable, that the formulae here investigated represent exactly and in all cases the response of the crop to added nutrients. What is claimed is that the method is capable of supplying information of immediate importance both about soil and about varieties and that only by much increased experimental precision can we hope to exhaust its possibilities or to discover in what respects further improvement is possible.

My best thanks are due to Dr R. A. Fisher of the Rothamsted Experimental Station, who suggested the problem, supplied most of the data and gave valuable guidance at every important stage. My thanks are also due to Dr Gregory of the Imperial College of Science and the authorities of the Seale-Hayne Agricultural College for kindly allowing me to make use of their data.

5. APPENDIX I.

Standard errors of the constants:
Maximum likelihood is given by

$$L = -\frac{1}{2\sigma^2} S\,(y-m)^2,$$

where y and m stand for the observed and expected yields respectively.

$$\therefore \quad \frac{\delta L}{\delta a} = \frac{1}{\sigma^2} S\left\{(y-m)\frac{\delta m}{\delta a}\right\},$$

or

$$-\frac{\delta^2 L}{\delta a^2} = \frac{1}{\sigma^2} S\left\{-(y-m)\frac{\delta^2 m}{\delta a^2} + \left(\frac{\delta m}{\delta a}\right)^2\right\} = \frac{1}{V(a)}$$

$$= \frac{1}{\sigma^2} S\left\{\left(\frac{\delta m}{\delta a}\right)^2 - (y-m)\frac{\delta^2 m}{\delta a^2}\right\},$$

$$\left[m = \frac{1}{c + \dfrac{a_n}{n+N}}, \quad \frac{\delta m}{\delta a} = -m^2 \cdot \frac{1}{n+N} \text{ and } \left(\frac{\delta m}{\delta a}\right)^2 = \frac{m^4}{(n+N)^2}\right].$$

The second term disappears, since the expectation of y equals m. Hence

$$-\frac{\delta^2 L}{\delta a^2} = \frac{1}{\sigma^2} S\left[\left(\frac{\delta m}{\delta a}\right)^2\right] = \frac{1}{\sigma^2} S\frac{m^4}{(n+N)^2},$$

$$\therefore \quad \frac{1}{V(a)} = \frac{1}{\sigma^2}\overset{4}{\underset{1}{S}}\frac{W}{(n+N)^2} \qquad \text{......(i).}$$

Similarly

$$\frac{\delta L}{\delta n} = \frac{1}{\sigma^2} S\left\{(y-m)\frac{\delta m}{\delta n}\right\},$$

$$-\frac{\delta^2 L}{\delta n^2} = \frac{1}{\sigma^2} S\left\{-(y-m)\frac{\delta^2 m}{\delta n^2} + \left(\frac{\delta m}{\delta n}\right)^2\right\} = \frac{1}{V(n)},$$

$$\left[m = \frac{1}{c + \dfrac{a_n}{n+N}}, \quad \frac{\delta m}{\delta n} = -m^2 \cdot \frac{-a}{(n+N)^2}\right].$$

$$\therefore \quad \frac{1}{V(n)} = \frac{1}{\sigma^2} S\left[\left(\frac{\delta m}{\delta n}\right)^2\right] = \frac{a^2}{\sigma^2}\overset{4}{\underset{1}{S}}\frac{W}{(n+N)^4} \qquad \text{......(ii).}$$

In the same way

$$\frac{1}{V(c)} = \frac{1}{\sigma^2} S\left[\left(\frac{\delta m}{\delta c}\right)^2\right] = \frac{1}{\sigma^2}\overset{4}{\underset{1}{S}} W \qquad \text{......(iii),}$$

$$\frac{1}{V(a,n)} = -\frac{\delta^2 L}{\delta a\,\delta n} = -\frac{a}{\sigma^2}\overset{4}{\underset{1}{S}}\frac{W}{(n+N)^3} \qquad \text{......(iv),}$$

$$\frac{1}{V(a,c)} = -\frac{\delta^2 L}{\delta a\,\delta c} = \frac{1}{\sigma^2}\overset{4}{\underset{1}{S}}\frac{W}{n+N} \qquad \text{......(v),}$$

$$\frac{1}{V(n,c)} = -\frac{\delta^2 L}{\delta n\,\delta c} = -\frac{a}{\sigma^2}\overset{4}{\underset{1}{S}}\frac{W}{(n+N)^2} \qquad \text{......(vi).}$$

If c and n were known *a priori*, the sampling variance of a would be $\frac{1}{L_{aa}}$, but if c and n are determined from the observations (6),

$$V(a) = \begin{vmatrix} L_{nn} & L_{nc} \\ L_{nc} & L_{cc} \end{vmatrix} \div \begin{vmatrix} L_{aa} & L_{an} & L_{ac} \\ L_{an} & L_{nn} & L_{nc} \\ L_{ac} & L_{nc} & L_{cc} \end{vmatrix},$$

where $$L_{aa} = -\frac{\delta^2 L}{\delta a^2}, \quad L_{an} = -\frac{\delta^2 L}{\delta a \delta n}, \text{ etc.}$$

Substituting the values of L_{aa}, L_{an}, etc. we get

$$V(a) = \frac{\begin{vmatrix} \frac{a^2}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{n+N} & -\frac{a}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{(n+N)^2} \\ -\frac{a}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{(n+N)^2} & \frac{1}{\sigma^2} S\, W \end{vmatrix}}{\begin{vmatrix} \frac{1}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{(n+N)^2} & -\frac{a}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{(n+N)^3} & \frac{1}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{n+N} \\ -\frac{a}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{(n+N)^3} & \frac{a^2}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{n+N} & -\frac{a}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{(n+N)^2} \\ \frac{1}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{n+N} & -\frac{a}{\sigma^2} \overset{4}{\underset{1}{S}} \frac{W}{(n+N)^2} & \frac{1}{\sigma^2} \overset{4}{\underset{1}{S}} W \end{vmatrix}}.$$

Similarly

$$V(n) = \begin{vmatrix} L_{aa} & L_{ac} \\ L_{ac} & L_{cc} \end{vmatrix} \div \begin{vmatrix} L_{aa} & L_{an} & L_{ac} \\ L_{an} & L_{nn} & L_{nc} \\ L_{ac} & L_{nc} & L_{cc} \end{vmatrix} \quad \text{etc.}$$

6. APPENDIX II.

POTATOES (KERR'S PINK), STACKYARD FIELD, 1926.

Average yield in tons per acre (y).

		Cwt. per acre sulphate of potash			
		0	1	2	4
Cwt. per acre sulphate of ammonia	0	7·80	7·80	8·01	7·79
	1	7·73	8·98	9·17	9·01
	2	9·40	10·56	10·30	10·44
	4	9·53	11·15	11·62	12·34

Reciprocals of expectations from Special Resistance Formula.

·14070	·12817	·12575	·12415	·02937
·11977	·10724	·10482	·10322	·00844
·11007	·09754	·09512	·09352	−·00126
·10084	·08831	·08589	·08429	−·01049
·11133	·09880	·09638	·09478	

Expectations from Special Resistance Formula (m).

7·10	7·80	7·95	8·05
8·35	9·33	9·54	9·69
9·08	10·25	10·51	10·69
9·92	11·32	11·64	11·86

$$\Sigma\,(y-m)^2 = 2{\cdot}3832$$

$k = 0{\cdot}48 \pm 0{\cdot}60$ $\qquad$ $n = 1{\cdot}738 \pm 0{\cdot}85$

$a_k = 0{\cdot}0089 \pm 0{\cdot}0129$ $\qquad$ $a_n = 0{\cdot}0986 \pm 0{\cdot}0616$

Analysis of variance	Degrees of freedom	Sum of squares	Mean square
Field error	45	48·510	1·078
General Formula—Treatments	6	124·914	20·819
	9	5·364	·596
	15	130·278	
Special Formula—Treatments	4	118·076	29·936
	11	12·199	·866
	15	130·275	

POTATOES (SEALE-HAYNE). (Dunged area, 10 tons of dung per acre.)

Average yield in tons per acre (y).

	Cwt. per acre sulphate of ammonia				
		0	1	2	3
Cwt. per acre sulphate of potash	0	4·85	6·18	7·38	7·37
	1	5·19	6·72	7·82	8·23
	2	5·46	6·81	7·37	7·95
	3	5·79	7·01	7·85	9·00

Reciprocals of expectations from Special Resistance Formula.

·19810	·16008	·14281	·13294	·01179
·18741	·14939	·13212	·12225	·00110
·18355	·14553	·12826	·11839	–·00276
·18155	·14353	·12626	·11639	–·00476
·18631	·14829	·13102	·12115	

Expectations from Special Resistance Formula (m).

5·05	6·26	7·01	7·54
5·34	6·70	7·58	8·19
5·45	6·87	7·79	8·45
5·50	6·96	7·91	8·58

$\Sigma\,(y-m)^2 = \cdot 9910$ in tons per acre

$= 776{\cdot}94$ in lb. per plot

$k = 1{\cdot}13 \pm 0{\cdot}58$ $\qquad$ $n = 1{\cdot}66 \pm 0{\cdot}40$

$a_k = 0{\cdot}0258 \pm 0{\cdot}0170$ $\qquad$ $a_n = 0{\cdot}1689 \pm 0{\cdot}0480$

Analysis of variance (in lb. per plot)	Degrees of freedom	Sum of squares	Mean square
Field error	45	19,260	428
General Formula—Treatments	6	59,712	9,952
	9	1,610	179
	15	61,322	
Special Formula—Treatments	4	58,216	14,554
	11	3,102	282
	15	61,318	

POTATOES (SEALE-HAYNE). (Undunged area, 1927.)

Average yield in tons per acre (y).

		Cwt. per acre sulphate of ammonia			
		0	1	2	3
Cwt. per acre sulphate of potash	0	3·20	4·30	4·13	4·56
	1	3·83	5·74	7·40	6·92
	2	3·68	5·11	6·92	6·91
	3	4·10	5·64	6·52	6·86

Reciprocals of expectations from Special Resistance Formula.

·33420	·25125	·23207	·22351	·07578
·24931	·16763	·14818	·13962	−·00811
·25470	·17202	·15257	·14401	−·00372
·25606	·17338	·15393	·14537	−·00236
·25842	·17574	·15629	·14773	

Expectations from Special Resistance Formula (m).

2·99	3·98	4·31	4·47
4·01	5·97	6·75	7·16
3·93	5·81	6·55	6·94
3·91	5·77	6·50	6·88

$$\Sigma (y-m)^2 = 1{\cdot}4965 \text{ in tons per acre}$$
$$= 750{\cdot}87 \text{ in lb. per plot}$$

$k = -{\cdot}10 \pm{\cdot}09$ $n = {\cdot}57 \pm{\cdot}22$

$a_k = -{\cdot}0075 \pm{\cdot}0064$ $a_n = {\cdot}0788 \pm{\cdot}0341$

Analysis of variance (in lb. per plot)	Degrees of freedom	Sum of squares	Mean square
Field error	45	14,549	323·3
General Formula—Treatments	6	55,298	9216·0
	9	1,726	191·8
	15	57,024	
Special Formula—Treatments	4	53,920	1348·0
	11	3,103	273·0
	15	57,023	

BARLEY POT CULTURES, ROTHAMSTED, 1927.

Average yields in gm. (*dry weight*) *per pot.*

		Nitrogen, mg. per pot				
		15	45	105	405	1215
P_2O_5 in mg. per pot	5	3·06	4·30	11·33	14·84	15·00
	15	3·36	5·77	12·44	19·38	17·88
	45	3·03	6·34	13·34	22·41	29·60
	105	3·39	6·64	14·33	36·30	68·10
	405	3·60	6·30	14·63	33·70	86·40

Reciprocals of expectations from Resistance Formula.

·33967	·19545	·11136	·07586	·06296	·04400
·32278	·17856	·09447	·05897	·04607	·02711
·30514	·16092	·07683	·04133	·02843	·00947
·29418	·14996	·06587	·03037	·01747	−·00149
·28939	·14517	·06108	·02558	·01268	−·00628
·29567	·15145	·06736	·03186	·01896	

Expectations from Resistance Formula (m).

2·94	5·12	8·98	13·18	15·88
3·10	5·60	10·59	16·96	21·71
3·28	6·22	13·02	24·20	35·17
3·40	6·67	15·18	32·93	57·24
3·46	6·89	16·37	39·09	78·86

$n = 13{\cdot}95$ $\quad$ $p = 16{\cdot}36$

$a_n = 8{\cdot}204$ $\quad$ $a_p = 1{\cdot}131$

Analysis of variance	Sum of squares	Degrees of freedom	Mean square (mean of 6·24 pots)
$1/\bar{y}^2\, S\,(y-\bar{y})^2$	3·3374	142	·00376
General formula $S\,(\log y - \log m)^2$	0·0472	16	·00295
Special formula $S\,(\log y - \log m)^2$	0·0607	19	·00319

REFERENCES.

(1) MITSCHERLICH, E. A. *Landw. Jahrb.* **49**, 335, 1916, to **58**, 1923.

(2) BRIGGS, G. E. Plant Yield and the Intensity of External Factors. *Ann. Bot.* **155**, July 1925, 475–502.

(3) LEMMERMAN, O. *Zeitschrift für Pflanzenernährung, Düngung and Bodenkunde.* VII Jahrgang, Februar 1928, Heft 2.

(4) FISHER, R. A. (1921). An Examination of the Yield of Dressed Grain from Broadbalk. *J. Agric. Sci.* **11**, 107–135. (Rothamsted Memoirs, II.)

(5) —— (1928). *Statistical Methods for Research Workers.* Oliver and Boyd.

(6) —— (1921). On the Mathematical Foundations of Theoretical Statistics. *Phil. Trans.* A, **222**, 309–368.

(7) RUSSELL, E. J. and RICHARDS, E. H. (1916). On making and storing farmyard manure. *J. Roy. Agric. Soc. Eng.* **77**, 9.

(8) SCHEIDEWIND, Prof. Dr W. (1922). *Die Ernährung der Landwirtschaftlichen Kulturpflanzen*, pp. 244–245.

(*Received June 20th*, 1928.)

EXPERIMENTS IN THE CULTIVATION OF THE SUGAR BEET CROP IN THE WEST MIDLANDS DURING 1927.

By W. MORLEY DAVIES, M.A. (Cantab), B.Sc.
(*Advisory Chemist, Harper Adams Agricultural College, Newport, Salop.*)

(With One Text-figure.)

Introduction.

Although the experiment described in this paper was undertaken in the first instance to obtain information on local conditions, the results are of general interest as an experiment in the effects of cultivation on the yield and returns of the sugar beet crop. The objects of the experiment were:

(*a*) To make a comparison of the effect on yield of growing the crop on the ridge with growing on the flat.

(*b*) To obtain data on the effect of spacing on the yield.

(*c*) To endeavour to give a financial expression to the results.

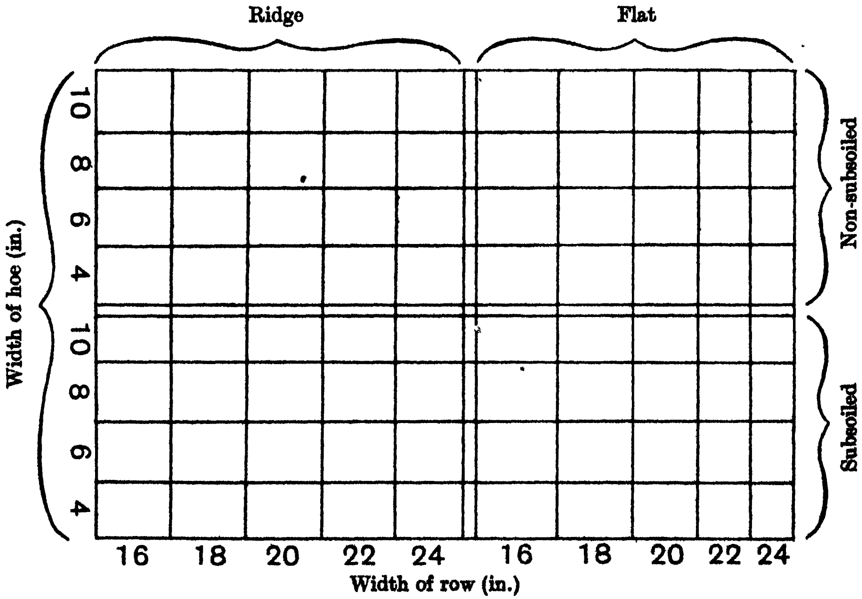


Fig. 1.

The lay out of the scheme is shown in Fig. 1; it allows for subsoiling and non-subsoiling on the ridge and on the flat, for five widths of rows and four widths of hoes. The whole area under experiment was 4 acres. This was divided into 80 one-twentieth acre plots.

Soil. The soil is a sandy loam, increasing slightly in heaviness in the lower part of the field; the upper part has a more open subsoil than the lower. Drainage conditions are on the whole good.

Cultivations. The whole field was subjected to the usual preliminary cultivation operations, ploughing, cultivating, rolling, harrowing. In addition there was the extra cultivation of subsoiling the lower part.

On the ridge. Sowing in the 16 in. drill was done by hand labour with a planet drill, and on the rest by the ordinary two-row turnip drill.

On the flat. Sowing was carried out with the corn drill.

Horse-hoeing. This was possible on all the different widths except the 16 in. drill where it was done by manual labour. This increased charge has been included in the estimate of costs.

Singling was started on June 9 and harvesting on November 14.

Manuring. Farmyard manure was applied to the potato crop in 1925 at rate of 16 tons per acre.

In 1926 swedes were grown with artificials only. The beet crop received artificials only at the following rate: 7 cwt. per acre of a mixture of 4 cwt. superphosphate 30 per cent., 1½ cwt. sulphate of ammonia, 1½ cwt. muriate of potash. Lime was applied at rate of 10 cwt. carbonate of lime per acre in 1926.

Harvesting. This was carried out as laid down in the Ministry of Agriculture memorandum for county experiments. Ten half-chain lengths per plot were used for obtaining the gross weight. Fifty beet weighed in the field were taken (five from each half-chain length) for estimation of dirt tare and sugar content. The sugar content was obtained by means of the le Docte rasp and the Krüger cold-water diffusion method.

Costing. Naturally the information most needed by the agriculturalist is an expression of the results of the experiment in terms of financial returns per acre. The Department of Economics has estimated the cost per acre of growing the sugar beet on a basis of certain fixed charges (cultivations and manuring) common to all plots and a variable charge for singling and hand-hoeing based on the number of plants per acre. Thirty shillings per acre was found to be the cost of 20½ in. rows and 7½ in. spacing on averaging forty-nine farms, and this figure has been varied in proportion to the spacing of the plants in the experiment under consideration.

While it is impossible to obtain actual costs on such small plots, it is believed that the above approximation gives fair relative values, and has the merit of a uniform variation over the whole experiment.

Calculations of the gross returns per acre have been found by taking tonnage per acre and sugar content, and applying the ruling factory prices for the season 1927.

Relative net profits are found by taking the difference between the gross returns and the costs per acre.

Four main sets of figures are therefore obtained for each plot:

(*a*) Tons per acre washed beet (T.p.a.).
(*b*) Sugar content (S.C.).
(*c*) Gross returns per acre (G.R.).
(*d*) Relative net profits per acre (R.N.P.).

Results of experiments.

Table I. *Ridge* v. *Flat.*

	Ridge	Flat
T.p.a.	13·41	12·14
G.R.	£37. 19*s*. 1*d*.	£33. 16*s*. 0*d*.
R.N.P.	£19. 17*s*. 7*d*.	£16. 10*s*. 7*d*.

The returns of tonnage, gross returns and relative net profits show an advantage in favour of growing on the ridge as against the flat (Table I). The difference is statistically significant.

The results on our own field are corroborated by the Staffordshire C.C. and the Shropshire C.C. results (Table II), where the advantage is in favour of ridge over flat (Table II).

Table II. *Ridge* v. *Flat.*

	Ridge	Flat	
St. C.C.	12·2	10·6	T.p.a.
Sh. C.C.	16·3	11·7	T.p.a.

Table III. *Subsoiled* v. *Non-subsoiled.*

Non-subsoiled	Subsoiled	
12·98	12·57	T.p.a.
£36. 2*s*. 4*d*.	£35. 12*s*. 9*d*.	G.R.
£18. 13*s*. 9*d*.	£17. 14*s*. 2*d*.	R.N.P.

There is no significant difference in the figures in Table III and the results do not appear to justify subsoiling in this field for the past season. It must be made clear however that the above figures cannot

be applied unreservedly to any other field, since there is ample evidence that subsoiling has proved beneficial in many cases. The danger in generalising cannot be too strongly emphasised, since the occurrence of a hard pan, a tough and closely compacted subsoil or poor drainage has in many instances justified subsoiling.

Table IV. *Width of rows.*

Rows (in.)	T.p.a.	G.R.	R.N.P.	S.C. %
16	14·96	£42. 5*s*. 2*d*.	£22. 4*s*. 8*d*.	16·6
18	13·46	£38. 3*s*. 4*d*.	£19. 18*s*. 1*d*.	16·6
20	12·01	£33. 5*s*. 3*d*.	£16. 13*s*. 8*d*.	16·0
22	11·96	£33. 11*s*. 6*d*.	£16. 15*s*. 2*d*.	16·4
24	11·49	£32. 2*s*. 5*d*.	£15. 11*s*. 7*d*.	16·2

The figures in Table IV represent the returns for the whole experiment and it should be noted are the returns for the quadruplicate series. All figures show an increase with narrower spacing of the rows and the evidence goes to show that an increased tonnage, with increased returns are obtained on the narrowest spacing. In obtaining the costs the 16 in. plots were charged with hand labour instead of horse-hoeing (representing an increased charge of 30*s*. per acre), and even then the 16 in. rows show a definitely increased return over the other rows. Statistically there is a significant difference between the 16 in. row and the remainder, between the 18 in. row and the remainder, but not between the 20 in., 22 in. and the 24 in. rows.

The evidence from other centres.

Sambrook and Honnington show a slight advantage in favour of the 20 in. row (spacing was 18 in., 20 in., 22 in. and 24 in.).

Taking Sambrook, Honnington and Harper Adams together the evidence is in favour of the 18 in.; it should be noted that the 16 in. spacing was not included at the two external centres.

County Council experiments (Table V) (18 in., 21 in. and 24 in.).

Table V.

Rows (in.)	St. C.C. T.p.a.	Sh. C.C. T.p.a.
18	16·25	10·15
21	11·5	9·4
24	12·65	9·2

In the case of these experiments, the heavier crops (over 10 tons

per acre) give the most marked advantage in favour of the 18 in. rows. Where the crop is lighter the differences are smaller (Table VI).

Table VI.

	St. C.C. and Sh. C.C.	
	Heavier crops	Lighter Crops
Rows (in.)	T.p.a.	T.p.a.
18	14·95	8·05
21	12·03	8·07
24	11·99	7·91

In both the County Council and the Harper Adams experiments the higher crop yields favour the 18 in., the 16 in. row being excepted.

The deductions from the evidence suggest that a heavy yielding crop (at any rate in a season like 1927) can only be obtained by narrow spacing of the rows. Should a farmer be content with a medium or light crop (which is unlikely) then spacing of the rows is of less importance.

Table VII. *Width of hoes.*

Hoes (in.)	T.p.a.	G.R.	R.N.P.
10	12·49	£34. 13*s.* 3*d.*	£17. 11*s.* 3*d.*
8	12·99	£36. 7*s.* 3*d.*	£19. 0*s.* 8*d.*
6	12·97	£36. 8*s.* 0*d.*	£18. 7*s.* 11*d.*
4	12·63	£36. 1*s.* 10*d.*	£17. 15*s.* 10*d.*

An examination of the returns per acre (Table VII) and relative net profits shows only little difference between the figures for the various widths of hoes. What little difference there is, is in favour of the 6 in. or the 8 in. hoe as against the 10 in. and 4 in.

The results from Sambrook and Honnington show very little difference between the various widths of hoes, such small difference however favours the 8 in. hoe.

It seems therefore that the width of hoe is of less importance than the width of row, and that the evidence is in favour of a medium width hoe.

The relation between tons per acre, sugar content, gross returns and relative net profits.

A closer examination of the four sets of data in Table IV shows a very interesting and important relationship.

Each increase in yield of washed beet with decreasing distance between the rows is faithfully reflected both in the gross returns and in the relative net profits. There is evidently a much closer relation between the gross returns and relative net profits and the tons per acre than with the sugar content. Growing on a spacing even as narrow as 16 in. seems

justifiable in spite of the considerably increased charges for hand-hoeing on account of the horse-hoeing being impracticable with this spacing.

Profits are determined by the size of the crop and not by the sugar content suggesting that the primary object in growing sugar beet should be to obtain the maximum tonnage.

CONCLUSIONS.

With the reservation that the results refer to one season only, the data reviewed seem to point to some general conclusions of considerable importance.

(*a*) On fields where the soil has no tendency to form hard lower layers the necessity for subsoiling is not apparent. The crop however is one for which deep cultivation is essential.

(*b*) Returns for sugar beet grown on the ridge as against flat show a distinct advantage in favour of the ridge, both in tons per acre and financially.

(*c*) The evidence shows a very decided advantage in favour of narrow spacing of the rows. This is also corroborated by external evidence from the data derived from the Staffordshire and Shropshire County Council experiments. While at present practical considerations unfortunately rule out the 16 in. row, it seems that expectation of high yields can only be justified by using an 18 in. spacing.

(*d*) The results suggest that the width of hoe is less important than the width of row. There is a slight bias in favour of the medium width hoe (6 in. or 8 in.).

(*e*) There is a marked relationship between tons per acre, gross returns and relative net profits. Under the present type of contract existing with the factories it seems that the all-important aim of the agriculturist should be to produce a heavy tonnage and leave the sugar content to take care of itself.

ACKNOWLEDGMENTS.

The writer wishes to acknowledge the willing help received from his colleagues in the departments of Agriculture, Economics and Statistics, without whose assistance the experiment could not have been carried out; thanks are also due to the Agricultural Organisers of Staffordshire and Shropshire for the use of their figures, and to Mr T. C. Ward who kindly carried out sections of the experiment.

(*Received May* 10*th*, 1928.)

DIGESTIBILITY TRIALS WITH POULTRY.

IV. THE DIGESTIBILITY OF CERTAIN VARIETIES OF OATS.

V. THE DIGESTIBILITY AND FEEDING VALUE OF BULRUSH MILLET.

By E. T. HALNAN.

(Poultry Nutrition Section, Animal Nutrition Institute, School of Agriculture, Cambridge.)

IV. THE DIGESTIBILITY OF CERTAIN VARIETIES OF OATS.

Oats, and oat by-products form a common constituent of poultry feeding stuffs. Most grain mixtures used for poultry feeding contain oats, the whole oat being used for semi-adult and adult birds, and groats or pinhead oatmeal for the very young stock. Most mash mixtures, in addition, contain ground oats or Sussex ground oats. Palatability tests indicate that oats are not readily appreciated by fowls, since if a mixture of grains be fed to fowls, the oats are almost invariably left until the other grains have been consumed. This apparent lack of palatability is supported by the experiences met with in feeding trials where oats constituted the sole article of diet. Thus Brown (1) found difficulty in obtaining satisfactory experimental conditions when feeding oats alone, the daily ingestion of grain in the oat feeding trials being considerably less than that in the maize feeding trials, the grain being fed *ad libitum* in both cases. Kaupp and Ivey (2), feeding oats to Buff Orpington hens, were only able to bring the test to a satisfactory conclusion in 50 per cent. of the cases, six hens out of twelve finishing the test. Similar difficulty was experienced in our own feeding trials in inducing a satisfactory consumption of oats, but after a few preliminary trials and by reducing the amount fed per head per day to 80 gm. the trials were successfully carried through.

The trials were carried out with three varieties of oats, Grey Winter, Black Bountiful and Scotch Potato, the varieties used being selected after consultation with Dr H. Hunter, who obtained the samples used in our tests, and for whose help the writer wishes to record his grateful thanks. White Leghorn cockerels were used as digestibility birds, and the general plan of analytical and experimental procedure outlined in previous communications (3) was followed.

(I) THE DIGESTIBILITY OF GREY WINTER OATS.

Two White Leghorn cockerels were used in this experiment, 80 gm. of oats per day per head being fed. The experimental collection period lasted 12 days. The data obtained were as follows:

Average composition of Grey Winter oats.

Moisture	11·09 %	Ether ext.	7·37 %
Protein	8·56	Fibre	7·76
N-free ext.	62·13	Ash	3·09

Average composition of excreta in gm. actual weight.

	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Am-moniacal nitrogen	Ether extract	Fibre	Ash
Bird 1	334·71	302·11	15·81	7·58	1·26	11·77	75·42	32·60
Bird 2	300·10	272·50	12·44	5·62	1·06	12·87	71·70	27·60

Average composition of dung in gm. actual weight (calculated).

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Bird 1	269·51	36·31	11·18	75·42	146·60
Bird 2	247·89	30·56	12·43	71·70	133·20

Digestibility coefficients of Grey Winter oats.

Bird 1

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
960 gm. oats contain	823·88 gm.	82·18 gm.	70·75 gm.	74·50 gm.	596·45 gm.
Dung contains	269·51	36·31	11·18	75·42	146·60
Digested	554·37	45·87	59·57	−0·92	449·85
Dig. coefficient	67·3 %	55·8 %	84·2 %	—	75·4 %

Bird 2

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
960 gm. oats contain	823·88 gm.	82·18 gm.	70·75 gm.	74·50 gm.	596·45 gm.
Dung contains	247·89	30·56	12·43	71·70	133·20
Digested	575·99	51·62	58·32	2·80	463·25
Dig. coefficient	69·9 %	62·8 %	82·4 %	3·8 %	77·7 %
Average dig. coefficient	68·6 %	59·3 %	83·3 %	—	76·5 %

(II) THE DIGESTIBILITY OF BLACK BOUNTIFUL OATS.

During this trial, the two White Leghorn cockerels consumed approximately 60 gm. of oats per head per day, the experimental collection period lasting 16 days. The data obtained were as follows:

Average composition of Black Bountiful oats.

Moisture	11·12 %	Ether ext.	6·43 %
Protein	10·10	Fibre	8·45
N-free ext.	61·01	Ash	2·89

Bird 1 consumed 1020 gm. during the period, and Bird 2 consumed 990 gm.

Average composition of excreta in gm. actual weight.

	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Am-moniacal nitrogen	Ether extract	Fibre	Ash
Bird 1	398·89	365·84	13·46	6·23	1·77	9·25	89·06	33·05
Bird 2	380·10	334·97	12·80	5·23	2·06	10·87	83·65	45·13

Average composition of dung in gm. actual weight (calculated).

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Bird 1	336·27	27·44	8·72	89·06	211·05
Bird 2	308·07	28·44	10·39	83·65	175·28

Digestibility coefficients of Black Bountiful oats.

Bird 1

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
1020 gm. oats contain	877·11 gm.	103·02 gm.	65·59 gm.	86·19 gm.	622·30 gm.
Dung contains	336·27	27·44	8·72	89·06	211·05
Digested	540·84	75·58	56·87	—	411·25
Dig. coefficient	61·7 %	73·4 %	86·7 %	—	66·1 %

Bird 2

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
990 gm. oats contain	851·30 gm.	100·00 gm.	63·66 gm.	83·65 gm.	603·99 gm.
Dung contains	308·07	28·44	10·39	83·65	175·28
Digested	543·23	71·56	53·27	—	428·71
Dig. coefficient	64·0 %	71·6 %	83·7 %	—	71·0 %
Average dig. coefficient	62·8 %	72·5 %	85·2 %	—	68·5 %

(III) The digestibility of Scotch Potato oats.

For the Scotch Potato oats digestibility trial 80 gm. of oats per head per day were fed. The collection period lasted over 16 days, each bird consuming 1280 gm. The data obtained were as follows:

Average composition of Scotch Potato oats.

Moisture	13·54 %	Ether ext.	5·72 %
Protein	12·13	Fibre	9·90
N-free ext.	56·24	Ash	2·47

Average composition of excreta in gm. actual weight.

	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Am-moniacal nitrogen	Ether extract	Fibre	Ash
Bird 1	534·24	499·13	27·20	14·04	3·01	14·13	129·26	35·11
Bird 2	511·91	480·76	25·93	11·94	2·88	14·79	118·35	31·15

Average composition of dung in gm. actual weight (calculated).

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Bird 1	436·02	49·00	12·99	129·26	244·77
Bird 2	426·09	59·19	13·81	118·35	234·74

Digestibility coefficients of Scotch Potato oats.

Bird 1

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
[illegible] contain	975·29 gm.	155·20 gm.	67·45 gm.	126·72 gm.	719·92 gm.
Dung contains	436·02	49·00	12·99	129·26	244·77
Digested	539·27	106·20	54·46	—	475·15
Dig. coefficient	55·3 %	68·4 %	80·7 %	—	66·0 %

Bird 2

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
ontain	975·29 gm.	155·20 gm.	67·45 gm.	126·72 gm.	719·92 gm.
Dung contains	426·09	59·19	13·81	118·35	234·74
Digested	549·20	96·01	53·64	8·37	485·18
Dig. coefficient	56·3 %	61·9 %	79·5 %	6·6 %	67·4 %
efficient	55·8 %	65·6 %	80·1 %	—	66·7 %

DISCUSSION.

The oat grain shows considerable variation in its chemical composition. Thus, according to Pott (4), the crude protein content of oats has been found to vary from 5·9 to 19·0 per cent., the fat from 2·1 to 10·5 per cent., the crude fibre from 4·1 to 19·8 per cent., and the N-free extract from 48·0 to 71·8 per cent. These differences in composition are largely attributable to differences of variety, climate and soil. Hunter (5), in experiments carried out in 1920 and 1921, demonstrated that considerable differences in the chemical composition of the same varieties of oats could be obtained from season to season, and in the particular varieties tested, the seasonal differentiation exerted a larger influence than the varietal differentiation. So far as the varietal differences are concerned, the chief factor controlling the variation in chemical composition of the whole grain appears to be the husk to kernel ratio. The chemical composition of the husk and kernel respectively are so different in character that any fluctuation in the proportion of the husk to kernel is bound to alter considerably the chemical composition of the whole grain. This varietal difference is shown quite clearly in the varieties used in the digestibility trials, and, as the fibre figures indicate, are due to the varying percentages of husk to kernel characteristics of these varieties. Indeed, the varieties were chosen with this object in view, in order to ascertain whether the presence of a thin, medium, or thick husk influenced the digestibility coefficients of the whole grain. In the wheat digestibility experiments previously carried out, it was found that the coefficients of digestibility were not appreciably altered, all varieties tested giving approximately the same coefficients of digestibility. In the case of the digestibility trials with oats, however, interesting differences in coefficients

of digestibility have been shown, and the figures indicate that these differences are associated with the varietal differences in fibre content. Thus, in the case of Grey Winter oats with a fibre content of 8·7 per cent.[1] the organic matter was 68·6 per cent. digestible and the N-free extract was 76·5 per cent. digestible, in the case of Black Bountiful oats with a fibre content of 9·5 per cent.[1] the organic matter was 62·8 per cent. digestible and the N-free extract was 68·5 per cent. digestible, and in the case of Scotch Potato oats with a fibre content of 11·4 per cent.[1] the organic matter was 55·8 per cent. digestible and the N-free extract was 66·7 per cent. digestible. The digestibility of the organic matter and N-free extract is clearly affected by the fibre content of the oat, the presence of fibre in the oat having a depressant effect on the digestibility of these two nutrients. This depressant effect is not shown, however, in the case of the protein and the fat.

From the point of view of the poultry farmer, it is evident that the question of the variety of oats to feed is a very important one. In the varieties tested, on a 12 per cent. moisture basis, 100 lb. of Grey Winter oats contain 58·3 lb. digestible organic matter, Black Bountiful 53·5 lb. and Scotch Potato oats 47·7 lb., *i.e.* a ton of Grey Winter oats contains 108 lb. more digestible matter than a ton of Black Bountiful oats, and no less than 238 lb. more digestible matter than a ton of Scotch Potato oats.

Summary.

1. Digestibility trials with oats, carried out with White Leghorn cockerels, indicate that certain varieties of oats are more suitable as sources of food nutrients for poultry than others.

2. In the trials carried out, Grey Winter oats proved more suitable than Black Bountiful or Scotch Potato oats for poultry feeding.

3. The suitability of varieties of oats for poultry feeding appears to be linked with the fibre content, and thin husked varieties appear to be most suitable for this purpose.

4. Oats do not appear to be very palatable to poultry.

References.

(1) Brown, E. W. *U.S. Department of Agriculture, Bureau of Animal Industry Bulletin No.* 56.

(2) Kaupp, B. F. and Ivey, J. E. *Technical Bulletin No.* 22, *North Carolina Agric. Experimental Station.*

(3) Halnan, E. T. *J. Agric. Sci.* **16**, 451.

(4) Pott, Emil. *Handbuch der tierischen Ernährung und der landwirtschaftl. Futtermittel.*

(5) Hunter, H. *Oats: their varieties and characteristics.* Ernest Benn, Ltd.

[1] Calculated on a dry matter basis.

V. THE DIGESTIBILITY AND FEEDING VALUE OF BULRUSH MILLET (*PENNISETUM TYPHOIDEUM*).

At the request of the Empire Cotton Corporation, an investigation into the value for poultry feeding of bulrush millet was undertaken by the Poultry Nutrition Section of the Animal Nutrition Institute. The variety supplied was obtained from a crop grown in the Maherera area from seed sent from Mitole in the Chikwawa district of the Lower Shire, Nyasaland, and belongs to the large naked seeded, early maturing, non-branching type known as *Pennisetum spicatum* syn. *Pennisetum typhoideum*. Careful comparison of the grain with a sample sent by A. H. Ritchie, Government Entomologist for Tanganyika showed that the variety grown in Tanganyika Territory was identical, so far as the grain is concerned, with that cultivated in Nyasaland. In Tanganyika the crop is known as Mwele, and the grain is called "uwele."

Description of grain.

The grain consisted of small seeds, 1000 seeds weighing 8·1 gm. The seeds were tear-drop in shape, deep pearl blue-grey in colour at the base with a straw coloured germ at the apical end. The seed coat was smooth and highly polished in appearance.

Palatability.

The palatability was tested by feeding the grain to cockerels, laying hens, and young chicks. In all cases the grain was eagerly consumed, and when fed mixed with other grains, the birds showed a distinct preference for the millet. The experience obtained with young chicks indicated that this grain should prove exceedingly useful for inclusion in chick mixtures. In the case of the birds undergoing the digestibility trials, this grain was used as the sole source of dietary. The ration fed was eagerly cleared up, and at the end of the trial the birds were in good thriving condition.

Digestibility.

For the digestibility trials, two White Leghorn cockerels were used. The trial lasted 20 days, 110 gm. of millet per day per bird being fed, in a morning and an afternoon feed. The details of the experimental and analytical procedures used in the trial are outlined in a previous communication (1).

Experimental data. Bulrush millet.

Period of experiment 16 days Food fed 1760 gm. per bird

Average composition of bulrush millet.

Moisture	10·75 %	Ether ext.	4·70 %
Protein	12·88	Fibre	1·59
N-free ext.	67·74	Ash	2·34

Average composition of mixed excreta in gm. actual weight.

	Dry excreta	Organic matter	Total nitrogen	Uric acid nitrogen	Am-moniacal nitrogen	Ether extract	Fibre	Ash
Bird 1	341·59	294·95	32·36	21·49	2·45	21·47	25·83	46·64
Bird 2	361·38	313·99	30·09	21·91	2·79	26·82	27·35	47·39

Average composition of dung in gm. actual weight (calculated).

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Bird 1	205·85	31·44	19·87	25·83	128·71
Bird 2	221·83	11·37	25·16	27·35	157·95

Digestibility coefficients of bulrush millet.

Bird 1

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Food contains	1529·62 gm.	226·69 gm.	82·72 gm.	27·99 gm.	1192·22 gm.
Dung contains	205·85	31·44	19·87	25·83	128·71
Digested	1323·77	195·25	62·85	2·16	1063·51
Dig. coefficient	86·5 %	86·1 %	75·9 %	7·7 %	89·2 %

Bird 2

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Food contains	1529·62 gm.	226·69 gm.	82·72 gm.	27·99 gm.	1192·22 gm.
Dung contains	221·83	11·37	25·16	27·35	157·95
Digested	1307·79	215·32	57·56	0·64	1034·27
Dig. coefficient	85·5 %	94·9 %	69·6 %	2·3 %	86·8 %
Average dig. coefficient	86·0 %	90·4 %	72·7 %	5·0 %	88·0 %

The results of the digestibility trials indicate that bulrush millet is readily digested by poultry, and is suitable for inclusion in the class of cereal grains generally accepted for poultry grain mixtures. As measured by the digestibility coefficients, bulrush millet compares very favourably with wheat of approximately similar composition. For ease of comparison, the data obtained in previous trials with wheat are here inserted.

	Average composition		Digestibility coefficients	
	Little Joss wheat	Bulrush millet	Little Joss wheat	Bulrush millet
Moisture	10·75 %	10·75 %	—	—
Protein	12·34	12·88	86·5 %	90·4 %
N-free extract	71·96	67·44	89·3	88·0
Ether extract	1·79	4·70	35·8	72·7
Fibre	1·51	1·59	4·8	5·0
Organic matter	87·60	86·91	86·4	86·0
Ash	1·65	2·34	—	—

In the samples taken the bulrush millet showed close approximation in composition to Little Joss wheat, except in the case of the ether extract. This difference in composition of the ether extract is followed by differences in digestibility coefficients, the ether extract in bulrush millet being 72·7 per cent. digestible as compared with the ether extract of Little Joss wheat, which was only 35·8 per cent. digestible. On this basis, bulrush millet should approximate in price that of wheat used for poultry feeding.

SUMMARY AND CONCLUSIONS.

1. Palatability tests with bulrush millet (*Pennisetum typhoideum*) indicated that this grain of Empire origin is in every way suitable as a food grain for poultry in all stages of growth.

2. Digestibility trials have proved that this grain is readily digested by poultry.

3. Bulrush millet, on a digestibility and composition basis, appears to approximate in feeding value to Little Joss wheat.

REFERENCES.

(1) HALNAN, E. T. *J. Agric. Sci.* **16**, 451.

(*Received May 25th*, 1928.)

SOME PRELIMINARY EXPERIMENTS ON THE VALUE OF SMALL QUANTITIES OF WHOLE COWS' MILK WHEN FED TO PIGS.

By A. H. BLISSETT and J. GOLDING.

National Institute for Research in Dairying (University of Reading).

In the course of some pig feeding experiments in another connection, half a pint of full cream milk was given per pig per day.

It was observed that this small quantity of fresh milk produced a noticeable difference in the rate of growth of the pigs even when the basal ration was balanced and contained milk protein, milk sugar and the ash constituents of milk in abundance.

This paper deals with a series of preliminary experiments in which half a pint of milk was given to experimental pigs. The growth of these pigs is compared with groups of control animals which, in each case, were receiving similar rations generally considered to be adequate and well balanced but in which no milk was included.

Experimental.

Exp. 1. In the first experiment the basal diet consisted of:

	Jan. 20–Mar. 4	Mar. 5–Apr. 12
Toppings	74·0 %	55 %
Barley meal	5·5 %	30 %
Dried separated milk	18·0 %	15 %
Animal charcoal	2·5 %	2½ lb. per 100 lb. mixture

In addition one ounce of calcium carbonate and 1 lb. of swedes were offered per pig per day.

Twenty Middle White pigs were selected and divided into five comparable lots of four pigs. In addition to the basal ration the pigs in the experimental lots received half a pint of milk per pig per day from different cows (1); a quart of milk being mixed with the food and water which was weighed and mixed in an earthenware crock for each lot after the morning feed. The pigs were fed twice daily at 8 a.m. and 4 p.m. They were weighed once a week at noon of the same day of the week.

The experiment lasted ten weeks, at the end of which period the pigs were sent to the butcher as they attained about 100 lb. live weight.

The live weight increases and food consumption are shown in Table I.

Table I.

	Initial live weight of pen (lb.) Jan. 20, 1927	Final live weight of pen (lb.) Mar. 29, 1927	Gain in 67 days (lb.)	Av. daily live weight gain (lb.)	Av. lb. dry matter consumed per lb. live weight increase
Control pen (1)	113·0	360·0	247·0	0·92	2·65
Plus ½ pint milk (2)	113·0	383·25	270·25	1·01	2·49
,, ,, (3)	113·25	378·25	265·0	0·99	2·55
,, ,, (4)	113·5	377·5	264·0	0·99	2·56
,, ,, (5)	113·25	383·5	270·25	1·01	2·49

Although the milk was fed as an addition to the ration the total pounds of dry matter in the milk and in the other foods supplied required to produce 1 lb. increase in live weight was less in all the lots of milk fed pigs.

Exp. 2. In this and in the following experiments the control pigs were fed on a normal ration generally believed to be adequate in all respects. In this case it consisted of:

Toppings	30 %
Barley meal	20 %
Maize meal	20 %
Bean meal	20 %
Decorticated groundnut meal	10 %
Estimated starch equivalent	68·9 %
,, digestible protein	14·2 %
Nutritive ratio	1 : 4·85

Steamed bone flour and calcium carbonate were mixed in the food at the rate of 1¼ lb. steamed bone flour and ¾ lb. calcium carbonate per 100 lb. mixture.

Six Middle White pigs from the same litter born on January 30, 1927, were available. They were divided into two lots of three pigs. Each pig was fed separately in specially constructed individual feeding pens previously described (2). The pigs were fed twice daily (8 a.m. and 4 p.m.). They were turned out into a grass paddock for one hour daily.

Three pigs were fed on the basal ration only. The three experimental pigs were given half a pint of fresh milk daily and two ounces less of the basal ration (two ounces of the meal being taken as the protein equivalent of half a pint of fresh milk).

The results to 90 lb. live weight are given in Table II. At this weight the ration was changed and the pigs kept on till bacon weight, but for comparison with the other experiments only these weights are given.

Table II.

	Initial live weight of pig (lb.) May 4, 1927	Final live weight of pig (lb.) June 7, 1927	Gain in 35 days (lb.)	Daily live weight gain (lb.)	Lb. dry matter consumed per lb. live weight increase
Controls					
Pig No. 1	57·5	91·5	34·0	0·97	2·68
Pig No. 3	60·5	93·0	32·5	0·93	2·81
Pig No. 5	41·0	77·5	36·5	1·04	2·53
Average of control pen				0·98	2·67
Plus ½ pint milk					
Pig No. 2	57·5	97·0	39·5	1·13	2·28
Pig No. 4	46·0	83·0	37·0	1·06	2·43
Pig No. 6	44·5	81·8	37·0	1·06	2·43
Average of ½ pint milk pen				1·08	2·38

Exp. 3. Twelve Large White × Middle White pigs from three litters were available; selected pigs were evenly divided into three lots of four pigs in each lot.

The basal diet consisted of:

Toppings	30 %
Barley meal	20 %
Maize meal	20 %
Bean meal	20 %
Extracted soya bean meal ...	10 %
Estimated starch equivalent	67·5 %
,, digestible protein	14·2 %
Nutritive ratio	1 : 4·75

Twenty cubic centimetres of cod-liver oil was added to the food of each lot of pigs daily to supply extra vitamins A and D. Swedes were given to supply vitamin C. Steamed bone flour and calcium carbonate were given as in the previous experiment.

Two lots received the control ration with no milk, and one lot the control ration plus half a pint of milk per pig daily.

The milk fed pigs cleared up their food much more readily than the control pigs.

The daily ration for each pen was as usual weighed each morning into a crock and mixed with 2 lb. of water per pound of meal, the milk replacing an equivalent volume of water.

The mixture was fed in the afternoon and on the following morning. Afternoon milk from tuberculin tested cows was used. The average daily percentage of fat was 5·05 per cent. The results are given in Table III.

Table III.

	Initial live weight of pen (lb.) Jan. 24, 1928	Final live weight of pen (lb.) Apr. 2, 1928	Gain in 69 days (lb.)	Av. daily live weight gain (lb.)	Av. lb. dry matter consumed per lb. live weight increase
Control (4 pigs)	108·75	395·0	286·25	1·04	2·52
Plus ½ pint milk (4 pigs)	109·0	420·5	311·50	1·13	2·39
Control (4 pigs)	111·25	403·0	291·75	1·06	2·47

Exp. 4. In this experiment half a pint of milk was fed separately to individual pigs at noon, two ounces of the basal ration in water being given to the control animals at the same time.

The ration was similar to Exp. 3 and the technique of individual feeding followed as in Exp. 2.

The results to porker weight are given in Table IV.

Table IV.

	Initial live weight of pig (lb.) Apr. 3, 1928	Final live weight of pig (lb.) May 15, 1928	Gain in 42 days (lb.)	Daily live weight gain (lb.)	Lb. dry matter consumed per lb. live weight increase
Controls					
Pig No. 1	50·0	97·25	47·25	1·13	2·39
Pig No. 3	50·0	100·0	50·0	1·19	2·26
Pig No. 5	44·50	95·25	50·75	1·21	2·23
Average of control pen				1·18	2·29
Plus ½ pint milk					
Pig No. 2	49·0	103·5	54·5	1·30	2·05
Pig No. 4	44·0	98·0	54·0	1·29	2·07
Average of ½ pint milk pen				1·29	2·06

SUMMARY.

The results of four experiments are described in which twenty-five pigs were fed on a ration containing half a pint of milk. Eighteen were fed on control rations, generally considered to be adequate, and of which in one series dried separated milk was a constitutent.

In every case the fresh milk produced an increase in live weight over the controls varying from 8 to 10 per cent. Less dry matter per lb. increase in live weight was consumed by the experimental pigs than by the controls.

The returns for half a pint of milk fed per pig daily expressed as pounds live weight gain per gallon of milk fed, were as follows:

Exp. 1.	1·28 lb.	Exp. 2.	1·60 lb.
Exp. 3.	1·28 lb.	Exp. 4.	1·76 lb.

The higher values in Exps. 2 and 4 may have been due to the fact that the pigs were individually fed but differed in that the milk was mixed with the food in Exp. 2 and fed separately in Exp. 4.

FURTHER EXPERIMENTS IN WHICH EXTRACTED SOYA BEAN MEAL WAS USED IN THE CONTROL RATION.

Since writing the above paper two experiments have been conducted in which the control ration consisted of:

Toppings	40 %
Barley meal	25 %
Maize meal	20 %
Extracted soya bean meal	15 %
Estimated starch equivalent	66·8 %
Estimated digestible protein	13·6 %
Nutritive ratio	1:4·9

Steamed bone flour was mixed in the food at the rate of 1¾ lb. per 100 lb. mixture.

Cut grass was fed until July 19th when lucerne was available.

The pigs were all fed wet twice daily at 8 a.m. and 4 p.m. and during the hot weather in July, extra water was supplied after each meal in separate troughs.

The milk was fed mixed with the feed as in Exps. 1, 2 and 3.

Exp. 5. Eight Large White × Middle White pigs were divided into two comparable pens of four pigs in each.

Pen No. 1 received meal ration only.

Pen No. 2 received 2 pints of milk daily in place of ½ lb. meal ration (*i.e.* ½ pint milk per pig in place of 2 ounces meal).

The results to small porker weight are given in Table V.

Table V.

	Initial live weight of pen (lb.) May 9, 1928	Final live weight of pen (lb.) June 19, 1928	Gain in 41 days (lb.)	Average daily live weight gain per pig (lb.)	Average lb. dry matter consumed per lb. live weight increase
Control (4 pigs)	155·25	325·0	169·75	1·04	2·29
Milk (4 pigs)	154·25	337·0	182·75	1·11	2·10

These differences of increased rate of growth and less dry matter consumption per lb. live weight increase disappeared when the pigs were carried on to bacon weight.

Exp. 6. Sixteen Large White × Middle White pigs from two litters were divided into four comparable lots of four pigs in each.

Pens 1 and 3 were on control diet and pens 2 and 4 on milk diet.

The results to small porker weight are given in Table VI.

Table VI.

Pen no.	Initial live weight of pen (lb.) June 26, 1928	Final live weight of pen (lb.) Aug. 7, 1928	Gain in 44 days (lb.)	Average daily live weight gain per pig (lb.)	Average lb. dry matter consumed per lb. live weight increase
1. Control	157·5	329·0	171·5	0·97	2·40
2. Milk	157·0	336·0	179·0	1·02	2·27
3. Control	157·0	332·0	175·0	0·99	2·36
4. Milk	157·0	336·5	179·5	1·02	2·27
Averages					
1 & 3. Controls	—	—	—	0·98	2·38
2 & 4. Milk	—	—	—	1·02	2·27

Summary of Exps. 5 *and* 6.

During the summer months when extracted soya bean meal was fed at the rate of 15 per cent. in the control ration, the percentage increase from the milk feeding was not so great as in experiments 1 to 4, being only 6·7 per cent. and 4·1 per cent. over controls.

The returns for half a pint of milk fed daily expressed as pounds live weight per gallon of milk fed were as follows: Exp. 5, 1·12 lb.; Exp. 6, 0·64 lb.

A recent paper by H. R. Davidson (5) has shown the beneficial value of extracted soya bean meal which may have been responsible for diminishing the returns from the feeding of half a pint of milk per pig daily in the two later experiments.

Conclusions.

Preliminary experiments are reported, in all of which marked differences were observed when half a pint of milk was fed in addition to well-balanced rations.

As in the case of Dr Corry Mann's work (3) on the addition of a small quantity of milk per day to the diet of growing boys, the milk appeared to supply some extra factor or factors.

The total dry matter consumed per lb. increase in live weight was diminished by the milk feeding. This supports Woodman's contention (4) that milk "may have a specific action in increasing the extent to which

a given food stuff is digested." Half a pint of milk per pig per day seems to be a suitable minimum quantity to give daily to porkers.

It is intended to continue to investigate this problem.

REFERENCES.

(1) Golding and Zilva (1928). *Biochem. J.* **22**, No. 1, p. 173.
(2) Golding and Morris. *Pig Breeders' Annual*, 1927, p. 39.
(3) Corry Mann. *Medical Research Council Report*, Special Series, 105.
(4) Woodman (Jan. 1925). *J. Agric. Sci.* **15**, 22.
(5) Davidson (1928). *J. Ministry Agric.* **25**, p. 409.

(*Received May 27th*, 1928.)

THE DETERMINATION OF MOISTURE IN WHEAT AND FLOUR.

A STUDY OF "MOISTURE TESTING" IN WATER OVENS AND ELECTRIC OVENS.

By E. A. FISHER and C. R. JONES.
(The Research Association of British Flour Millers, St Albans.)

(With Six Text-figures.)

THE moisture content of materials such as wheat and flour is a characteristic of the utmost practical importance, but its determination is in no sense a straightforward matter and much attention has been given to the problem in the past. It is not possible to obtain by oven drying true values for the moisture content. What is sought is a convenient and reliable procedure giving strictly reproducible figures possessing full comparative value.

All the methods so far used for determining the moisture content of wheat and flour, with one exception, consist essentially of weighing a sample, driving off its moisture by drying under various conditions, weighing again and reckoning the loss in weight as the actual moisture content. The methods of drying tried can be classified as follows:

(1) Drying for a period, usually 5 hours or longer, in a water-heated oven.

(2) Drying for a period, usually 5 hours or longer, in an air-heated oven at a temperature of 100° C., or above.

(3) Drying in vacuum ovens at various temperatures and pressures.

(4) Drying *in vacuo* without heat.

(5) Drying in a stream of hydrogen or other "inert" gas in order to prevent oxidation of flour during drying.

The one exception is the Distillation Method, in which the grain is heated in a distillation flask with a hydrocarbon oil and the water that distils over is collected and measured. This method is distinguished from those listed above by the important feature that the moisture content is determined *directly*, by collecting and measuring the quantity of water obtained from a given amount of sample, instead of indirectly, as in the other methods where the loss in weight of the sample is reckoned as

moisture. Distillation methods are not usual in this country, although the Brown-Duvel method is the official method in U.S.A. for the moisture testing of *wheat* but not of *flour*. It involves a strict, but purely empirical, procedure, and has been carefully standardised against the water-oven method (see Coleman and Boerner (3); also Bidwell and Sterling (2), who use a simple application of the principle).

In this country the moisture content of wheat and flour is practically always determined either in a water-heated oven, or in an electrically-heated air oven. The present communication is concerned with a study of these two methods. Vacuum ovens are not in common use.

Factors affecting Oven Methods.

Large variations frequently occur in determining the moisture content of the same flour under different conditions and at different times; variations too frequently occur when the same sample is tested in much the same way by different workers, or even by the same workers on different occasions (see especially L. E. Leatherock (4); also American Committee (1), Shutt and Moloney (6), Snyder and Sullivan (8), Spencer (9)).

Some factors which may be expected to affect the results obtained by particular methods of oven testing are, for example, the temperature at which the drying is conducted and the length of time for which it is carried out, the size of sample taken, the conditions under which the samples are cooled, and so on. These factors have been dealt with by the workers referred to above; those which appeared to be the most significant have been carefully investigated in the writers' laboratory.

Type of Oven.

Undoubtedly the matter of primary importance is the choice of oven in which the drying is to be conducted, not only because the registered working temperature of one type of oven may differ from that of another, but because the drying efficiency of one may be greater, possibly because of different ventilation, but chiefly because of differences of effective temperatures. More especially, the effective temperature of a given oven may vary considerably in different parts of its interior—with the result that a large number of replicate samples of the same flour, dried for the same period at the same time in the one oven will show wide differences in water content. This "position effect" has been studied by numerous workers including Leatherock (4), Shutt and Moloney (6), Smith and

Mitchell (7). Such variation is notorious with most types of water-jacketed oven, apart altogether from the characteristically low results which they give compared with electrically-heated air ovens run at customary temperatures.

A COMPARATIVE STUDY OF WATER OVENS AND ELECTRIC OVENS.

Five-gram grab samples were used in all cases (unless otherwise stated) and the drying was carried out in aluminium tins, 2½ in. in diameter and ¾ in. deep. The period of drying was the same in both ovens, viz. 15 hours for wheat (which had previously been ground in a small coffee mill) and five hours for flour, semolina, etc. The water oven used was a large water-jacketed one heavily lagged on the outside with asbestos. There were three separate compartments, a large one below and two smaller ones above. The liquid used in the hollow walls of the oven was a mixture of water and glycerine, which boils at a temperature above 100° C. In spite of this the temperature inside the oven was always considerably below 100° and was not the same in each compartment. On one day for example, the temperature indicated in the lower compartment was 93·5°, that in the upper left-hand compartment was 94·2°, and that in the upper right-hand compartment was 90·3°.

The electric oven used was supplied by Charles Hearson and Co. It possessed efficient automatic temperature control and its temperature from day to day rarely altered by more than ± 1°.

The variations in temperature in different parts of the electric oven were not determined, but must have been extremely small since, as shown in Fig. 1, when the oven was filled with 31 replicates, the agreement between the results was good. The results need not be given in detail but are summarised below. The two methods gave entirely different results, those for the water oven being always lower than those obtained in the electric oven: these differences ranged in value from 0·61 to 2·43 per cent. and were distributed as follows:

Mean difference for wheat (20 pairs of samples)	1·97 %
,, ,, flour, semolina, etc. (25 pairs of samples)	1·92 %
,, ,, bran and middlings (10 pairs of samples)	1·67 %
,, ,, all 55 pairs of samples	1·89 %

Table I summarises the results of heating 24 replicates of the same flour sample at the same time for 5 hours in the water oven the thermometers of which indicated temperatures varying from 90·3° to 94·2° C. The moisture contents varied from 11·07 to 12·96 per cent., the mean of the 24 replicates being 12·05 per cent.

Table I. *Apparent moisture contents of 24 replicate flour samples heated in water-jacketed oven.*

Part of water oven	No. of replicates	Moisture content (%) Minimum	Maximum	Mean
Upper left-hand compartment				
Top shelf	3	12·73	12·81	12·78
Lower shelf	3	12·87	12·93	12·91
Upper right-hand compartment				
Top shelf	3	12·89	12·96	12·92
Lower shelf	3	12·25	12·27	12·26
Bottom compartment				
Top shelf	6	11·07	11·40	11·25
Lower shelf	6	11·11	11·83	11·52
Oven as a whole	24	11·07	12·96	12·05

Some water ovens give better results than this one which appears to be particularly unsatisfactory. One of the best that has come to the writers' notice was a small electrically heated water-jacketed oven in use at another laboratory. In this oven a sample of flour supplied by the writers was tested*. Eighteen replicate samples were placed in the oven at the same time, nine on each of the two shelves and the period of heating was 6 hours. The results were as follows:

Top shelf, moisture content varied between 14·20 and 14·48 per cent., mean being 14·36 per cent.

Bottom shelf, moisture content varied between 14·34 and 14·50 per cent., mean being 14·42 per cent.

In this case the agreement between replicates was very satisfactory but the mean value was almost exactly 1 per cent. lower than that obtained (15·36 per cent.) in the writers' electrically-heated air oven (6 hours at 110°). The apparent moisture content of the samples increased slightly from the front to the back of this oven. Thus the samples near the door gave moisture contents lower by 0·08 to 0·26 per cent. than those of the corresponding samples at the back of the oven.

These results with the water oven are in general agreement with those obtained by other workers. For routine purposes the electric oven is undoubtedly superior to the water-jacketed oven, for not only are the results obtained by its use consistently higher than those obtained with the water oven, but, as shown by Table II, the results are far more regular and reproducible. Moreover, as indicated in Fig. 1, there is very little position effect in this type of electric oven. All the determinations listed in Table II were carried out on the same 7 lb. sample of flour stored in a tin can with a close fitting friction lid. No attempt was made

* The writers' thanks are due to Dr D. W. Kent-Jones for carrying out these tests.

to hermetically seal the can and it is unsafe to assume that the real moisture content remained unchanged throughout. At the same time, the change must have been extremely small: out of 97 determinations made at 110° C. in a period of nearly eight weeks, the extreme variation

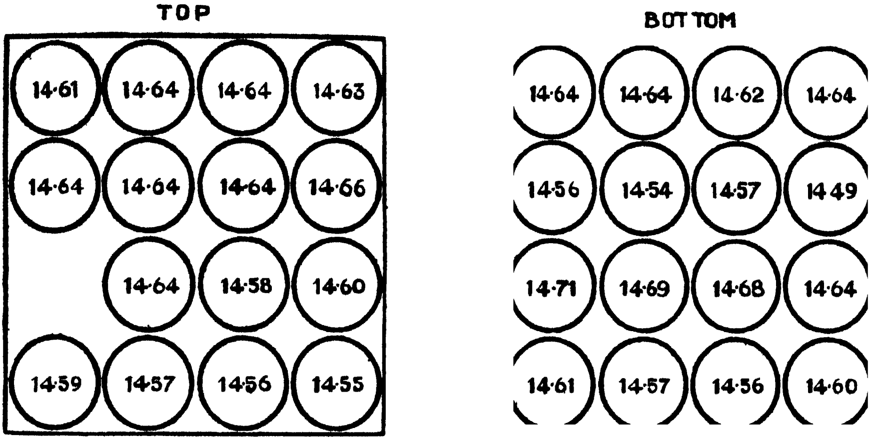


Fig. 1. Showing effect of position of sample in oven on apparent moisture content of flour (electric oven). $T=110°$ C.

Table II. *Moisture contents of replicate flour samples heated in electric oven.*

Date 1925	Temperature (° C.)	Shelf	No. of replicates	Moisture content (%) Minimum	Maximum	Mean
Mar. 10	110	Bottom	11	14·68	14·89	14·81
„ 21	110	Top	11	14·90	14·99	14·945
„ 23	105	Top	11	14·69	14·78	14·73
„ 26	110	Bottom	11	14·87	14·97	14·93
„ 30	110	Top	6	14·80	14·85	14·83
„ 30	110	Bottom	6	14·74	14·85	14·81
Apr. 27	110–111	Top	5	14·76	14·85	14·80
„ 27	110–111	Bottom	4	14·75	14·85	14·82
May 2	110–111	Top	6	14·77	14·83	14·80
„ 2	110–111	Bottom	6	14·74	14·85	14·80
„ 5	110	Top	15	14·55	14·66	14·61
„ 5	110	Bottom	16	14·49	14·71	14·61

The same sample of flour was used for all the above determinations. A wire netting shelf was used in all except the four series on April 27 and May 2, for which a solid galvanised iron shelf was employed.

observed was 0·50 per cent. (from 14·49 to 14·99 per cent.), the extreme variation on any single day was 0·22 per cent. (May 5), while the extreme variation between the means was 0·335 per cent. The slightly low value of 14·61 per cent. obtained on May 5 as the mean of 31 replicates may be due to a slight decrease in the real moisture content of the flour due

to the incidence of hot weather, or possibly to the very considerable amount of vapour produced in the oven by so many samples drying at the same time.

It does not follow that the result obtained by heating flour for 5 hours at 110° in an electric oven will be a correct measure of the real moisture content of the flour, but the data presented in Table II and Fig. 1 indicate that reliable and reproducible results can be obtained by the use of such an oven.

Study of the Electric Oven Method.

Effect of temperature and period of heating on the determination.

Work by the Committee on Methods of Analysis for the American Association of Cereal Chemists (1) showed that the difference between the results at 100° and at 105° was practically inappreciable, but that heating at 110° gave consistently higher results than the same procedure at 105°. The mean difference found for all samples dealt with was 0·24 per cent. On the other hand, Leatherock's (4) results were inconclusive; one series indicated appreciable difference between 105° and 100° but very little difference between 110° and 105°; the second series showed the reverse, *i.e.* appreciable difference between 110° and 105°, but quite inappreciable differences between 105° and 100° C.

Results obtained in the writers' laboratory, summarised in Table II, show that the mean of 11 replicate samples at 105° was 14·73 per cent., while the mean of all samples (97 samples on seven different days) at 110° was 14·80 per cent.

The results of a more detailed study are given in Table III.

This work was undertaken to ascertain the effects not only of different temperatures, but also of drying for different lengths of time, on flour and wheat. How long should samples be dried at any particular temperature in order to secure a reliable result? It was formerly assumed that continued drying caused the apparent moisture content to increase up to a point (the so-called "constant weight") and then to decrease owing to oxidation. The work of Shutt and Moloney seemed to show that for flour under properly controlled conditions, this decrease did not occur at 100° and 110°. Is this the case at other temperatures and for ground wheat also? Is a constant result obtained after heating for a certain length of time at any temperature? If so, is it possible, by employing higher temperatures, to reach the stage of constant weight after a shorter period of heating, thus saving time over the whole

operation; and does this constant result differ for different temperatures? If so, to what extent? If it is necessary to run an oven at any one particular temperature, for what length of time should samples be heated in order to obtain results comparable with those obtained at some other temperature?

The method followed was as follows: several pounds of a high grade patent flour was well mixed and kept throughout the work in a large air-tight tin with a closely fitting lid. Several pounds of a lot of No. 1 N. Manitoba wheat were similarly kept and sufficient small quantities ground in a small coffee mill before each weighing.

Table III. *Apparent moisture contents of replicate flour samples heated in electric oven at different temperatures and for different times.*

Temp. (° C.)	Date	Length of time in oven (hours) and moisture contents (%) (Each moisture figure represents average of duplicate determinations)								
Ground wheat		1	2	3	4	5	6	7	8	24 hrs.
95	July 27	10·70	11·94	12·26	12·77	12·87	12·94	12·37	12·65	13·37
100	June 15	11·15	—	12·66	12·90	12·85	12·92	—	—	13·28
	„ 18	11·39	11·88	12·04	12·42	12·46	12·96	12·94	13·52	13·45
	July 23	11·06	11·52	12·50	12·88	12·93	13·09	13·11	13·26	13·17*
105	June 25	11·68	12·20	13·02	12·96	13·18	13·32	13·52	13·57	13·14
	„ 26	10·91	12·45	12·94	13·08	13·05	13·36	13·49	13·52	13·90
	July 24	11·56	12·52	12·87	13·11	13·13	13·21	12·87	13·05	13·66*
110	June 19	11·57	12·49	12·76	13·13	13·33	13·34	—	—	13·72
	„ 24	11·60	12·84	13·04	13·45	13·46	13·61	13·78	13·77	13·77
	July 22	11·58	12·57	12·87	13·40	13·38	13·42	13·53	13·59	13·72
115	June 29	11·08	12·53	12·86	13·32	13·38	13·64	13·90	14·02	14·37
	„ 30	12·49	12·97	13·19	13·23	13·37	13·73	13·74	13·76	13·93
	July 21	12·44	13·11	13·36	13·69	13·64	13·67	13·82	13·85	13·95*
120	July 2	12·61	13·21	13·35	13·65	13·74	13·92	14·04	14·40	14·24
	„ 20	12·47	13·29	13·17	13·67	13·73	13·84	13·87	13·92	14·12*
130	July 7	12·61	13·35	13·66	13·95	14·06	14·12	14·35	14·02	14·23
	„ 9	11·30	12·30	12·74	12·98	13·29	13·31	13·39	13·44	14·30
Flour										
100	June 12	12·60	13·66	13·91	14·05	14·02	14·00	—	—	14·37
105	May 7	12·69	14·24	14·57	14·60	14·63	14·67	—	—	14·65
110	May 6	13·69	14·55	—	14·70	14·25	—	—	—	14·77
	„ 11	—	13·21	14·40	—	14·68	—	—	—	—
115	May 23	14·23	14·58	14·61	14·63	14·64	14·68	—	—	14·92
120	July 3	13·84	14·52	14·52	14·65	14·64	14·61	14·63	13·56	14·85
130	July 6	14·54	14·67	14·76	14·78	14·80	14·86	14·92	—	14·60
	„ 8	14·40	14·87	14·57	14·88	—	14·97	14·97	14·97	14·17

* 18 hours.

About 5 gm. of the flour, or ground wheat, was placed in the container (weighed immediately before and after loading) which was then placed in the oven with its cover removed and resting against the container.

After its proper time in the oven, each container was covered and allowed to cool for 20 minutes in a desiccator over sulphuric acid before weighing.

One oven was employed and a typical day's run at any one temperature would be as follows: duplicate samples were put in at 10.0 a.m. for 8 hours, and taken out at 6.0 p.m.; two others at 10.20 for 24 hours (*i.e.* till 10.20 next morning); two at 10.35 till 5.35; two at 10.50 till 4.50; two at 11.10 till 4.10; and four pairs at 12.0, one pair being taken out at 1.0, the second at 2.0, the third at 3.0 and the fourth at 4.0 p.m. All determinations were made in duplicate.

Examination of the results given in Table III shows that, though satisfactory agreements were obtained in some instances, no conclusions can safely be drawn from them. Consideration of the results suggested that one source of error lay in the fact that the oven was opened for insertion and removal of samples while other samples still remained in the oven—part way through their heating period. The variable cooling of the oven interior and interference with the temperature control might give rise to serious errors. This conclusion was supported by the closely concordant results of a trial in which two lots of triplicate samples were heated *consecutively* at 130° for 1 hour and 5 hours respectively. The 1 hour lot was placed in the oven at 10.30 a.m. and taken out at 11.30, the 5 hour lot being then placed in immediately and taken out at 4.30. The results were as follows:

1 hour lot	14·89	14·85	14·83
5 hour lot	14·92	14·92	14·89

It was decided, too, that duplicate determinations were insufficient to obtain really reliable final results and that in further study any accepted value must represent the average of as many determinations as possible (twelve was actually chosen as the most convenient number). The use of duplicate determinations only has undoubtedly been one cause of the striking lack of agreement between conclusions arrived at by different workers on this problem of moisture determination.

Accordingly the work was repeated on a more comprehensive scale. Two similar ovens were operated together. The different periods of heating were run consecutively, finished samples being removed from, and fresh ones put in both ovens simultaneously. Three replicate samples of flour and three of ground wheat were in each oven at any one time—twelve in all in the two ovens. The periods of heating were 1, 2, 3, 4, 5,

6, 12 and 14 hours respectively at each temperature. These were fitted in according to the following plan:

	Period of heating (hours)	Time entering oven	Time leaving oven
1st day	4	10.30 a.m.	2.30 p.m.
	1	2.30 p.m.	3.30 p.m.
	5	3.30 p.m.	8.30 p.m.
	14	8.30 p.m.	10.30 next morning
2nd day	2	10.30 a.m.	12.30 p.m.
	3	12.30 p.m.	3.30 p.m.
	6	3.30 p.m.	9.30 p.m.
	12	9.30 p.m.	9.30 next morning

Thus, 2 days were required to work through each temperature. Then each series was repeated at each temperature so that for any one period at any temperature twelve replicate results were obtained.

The work was further arranged so that the different temperatures on the two ovens overlapped by two days: *e.g.* oven *A* was started at 110° on Monday, September 7, and ran at that temperature till Thursday, the 10th (inclusive). Oven *B* was started at 110° on Wednesday, the 9th. On Friday, *A* proceeded to 105°. On Monday *B* proceeded to 105°—and so on through the range of temperatures. This arrangement eliminated any possibility which might be feared of the results being affected by varying humidity conditions and other uncontrolled factors. For not only were direct comparisons obtained between results obtained in the two ovens running simultaneously, side-by-side, at two different temperatures, but exactly corresponding determinations (at the same temperature) were done at intervals as far apart as 4 days. This latter point is important because, although the wheat and flour used in this work were stored in large glass bottles with well-fitting ground-glass stoppers (which were only removed whilst the samples were being taken), a careful check determination done towards the end of the work under the same conditions as one of the determinations done at the beginning (6 hours at 110°) showed an increase in the moisture content of the wheat of 0·23 per cent. This change would point to two possibilities: either that there had been a very gradual, continuous increase in the moisture content of the sample amounting to 0·23 per cent. over the whole period, which, distributed as it was, may be neglected without loss of accuracy; or that the moisture content had fluctuated erratically. The latter possibility would lead to some uncertainty in the interpretation of the results, but it is eliminated by the fact that corresponding determinations, made as described above at intervals as far apart as 4 or even 6 days, showed satisfactory agreement.

Fig. 2 affords an example of the kind of agreement between results obtained at the same temperature in different ovens at the same time, and in the same oven on different days. Curve I represents the averages of the triplicate determinations on flour at 105° in oven *B* on September 14 and 15, and Curve II those in oven *A* on the same days. Curve III represents those in oven *A* on the 16th and 17th. In other

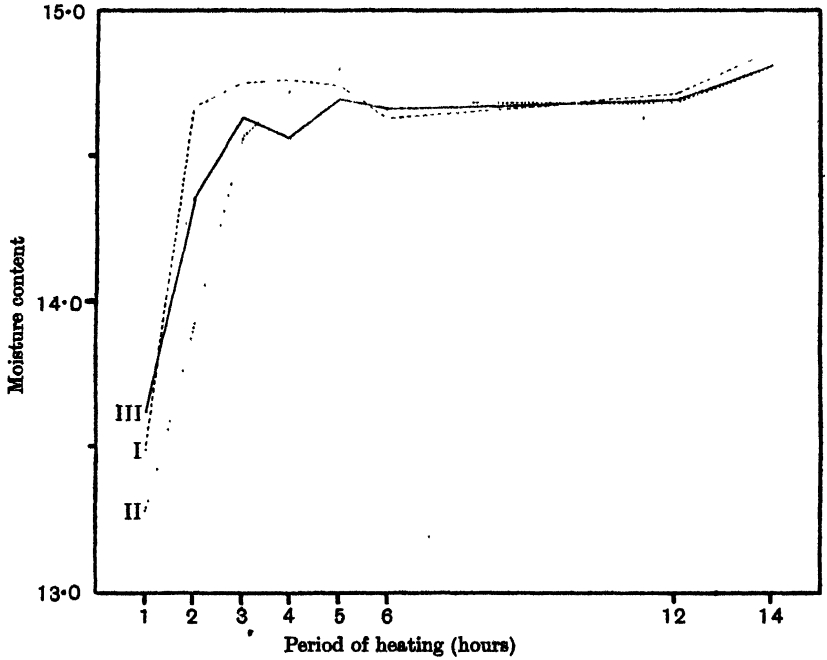


Fig. 2. Apparent moisture content of a flour determined at 105° C. (*a*) in different (electric) ovens on the same day, and (*b*) in same oven on different days.
Curve I shows results obtained with oven *B* on September 14 and 15.
Curve II shows results obtained with oven *A* on September 14 and 15.
Curve III shows results obtained with oven *A* on September 16 and 17.

words, Curves I and II afford a comparison of the two electric ovens (identical size and pattern) at 105°, and Curves I and III afford a comparison of the behaviour of the same oven at 105° on different days. It will be observed that there are decided differences between the means of triplicates in the different ovens and also in the same oven on different days for the shorter periods of heating. After 5 hours' heating these differences become inappreciable, *i.e.* less than 0·1 per cent.; or, to express it somewhat differently, for 5 or more hours' heating the results obtained in two different Hearson ovens on different days

should not vary more than the same number of results obtained in the same oven on the same day. For higher temperatures, *e.g.* 120° and above, the differences were inappreciable from the start.

The results obtained are given in Tables IV and V and graphed in Figs. 3 and 4. Each average result represents the mean of the twelve determinations; and, in addition, the maximum and minimum individual determinations are shown in the Tables.

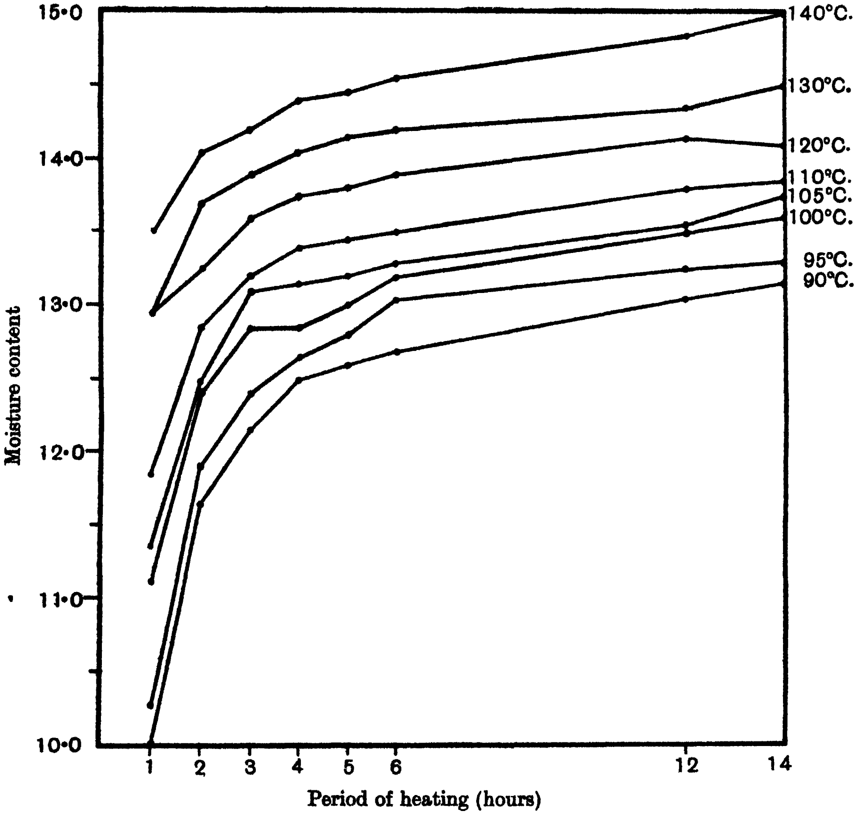


Fig. 3. Apparent moisture content of a sample of ground wheat as determined at different temperatures and with different periods of heating (electric oven).

It was considered worth while to examine statistically the data given in Table V. It is obvious from the curves of Figs. 3 and 4 that, in spite of the 68 dozen moisture determinations carried out on the same sample of wheat and of flour at different temperatures and different periods of heating, we do not know within 1 per cent. what the true moisture contents of the two samples were. At the higher temperatures, *e.g.*

120° and above, a slight darkening of the flour samples occurred during the heating, due presumably to slight dextrinisation of the starch. This was most pronounced at 140°, and indicated that at these temperatures matter other than moisture was being lost. We cannot, therefore, hope to find a true value for the moisture content by any method of oven drying at ordinary atmospheric pressures. This, however, is not important

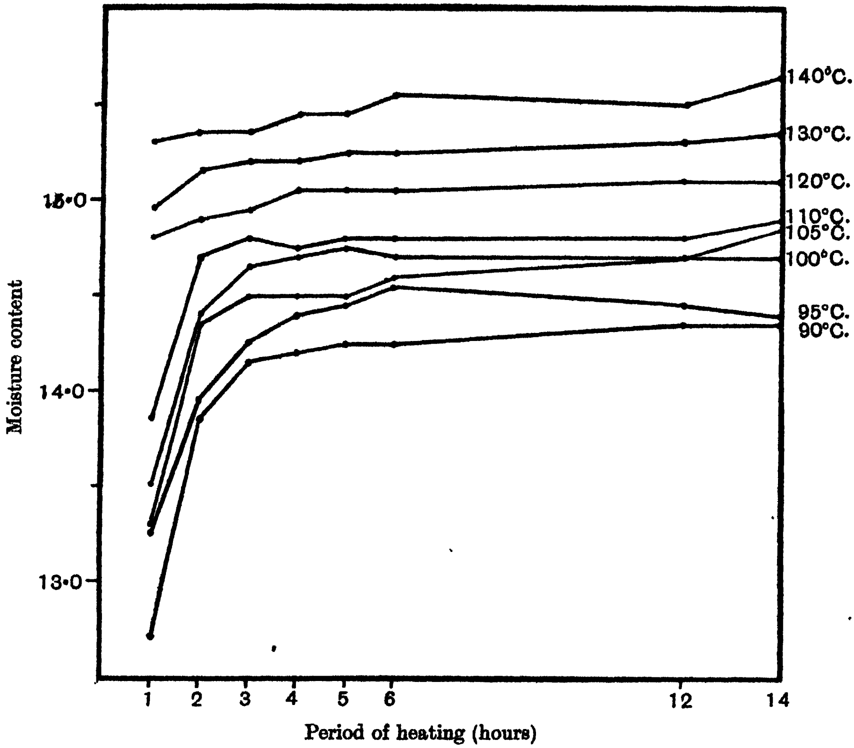


Fig. 4. Apparent moisture content of a sample of flour as determined at different temperatures and with different periods of heating (electric oven).

practically; what is of importance to the miller is that the results obtained should be reproducible from day to day within fairly narrow limits. If a sufficient number of replicate samples is dealt with it is possible to calculate the *probable errors* of each mean result and of each single determination. Twelve replicates however are too few to be examined in this way. An examination, admittedly approximate but sufficiently accurate for the present purpose, was made as follows:

It will be noticed from Table V that the 84 results of 6 and 12 hours' heating at 100° and of 3, 4, 5, 6 and 12 hours' heating at 105° were

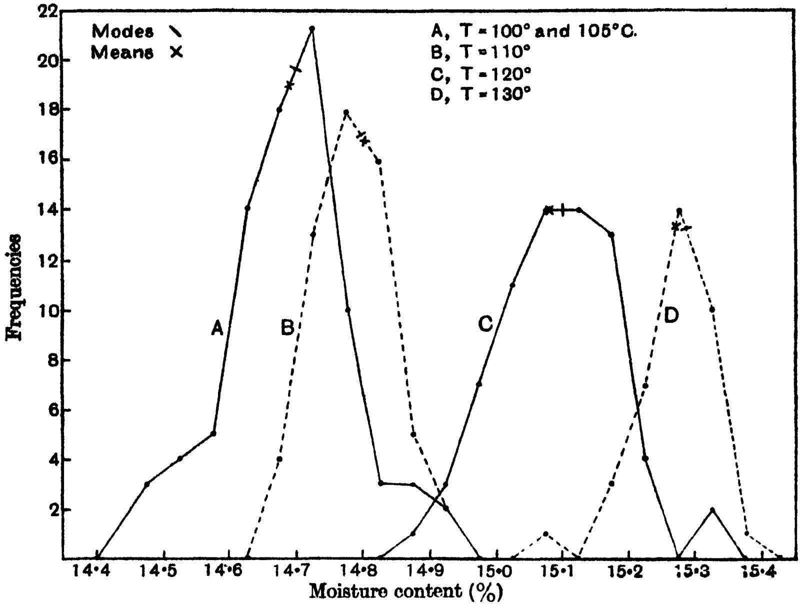


Fig. 5.

Table IV. *Showing maximum, minimum and average values of each twelve replicate determinations of moisture content at each temperature for each period of heating for ground wheat.*

Temp. (° C.)		Period of heating (hours) and moisture content (%)							
		1	2	3	4	5	6	12	14
90	Maximum	10·53	11·82	12·34	12·68	12·68	12·80	13·09	14·03
	Minimum	9·46	11·41	11·95	12·40	12·48	12·64	12·99	12·25
	Average	10·01	11·64	12·16	12·51	12·59	12·71	13·05	13·17
95	Maximum	10·94	12·13	12·55	12·79	12·99	13·13	13·49	13·45
	Minimum	9·53	11·71	12·15	12·43	12·58	12·96	13·05	13·17
	Average	10·23	11·91	12·40	12·66	12·81	13·04	13·24	13·28
100	Maximum	11·67	12·70	13·24	13·02	13·14	13·26	13·68	13·68
	Minimum	10·27	12·19	12·53	12·61	12·80	13·03	13·42	13·43
	Average	11·10	12·42	12·83	12·84	13·01	13·18	13·50	13·59
105	Maximum	11·77	12·83	13·24	13·35	13·37	13·57	13·68	13·86
	Minimum	10·85	12·06	12·76	12·92	13·11	13·19	13·46	13·51
	Average	11·34	12·51	13·11	13·13	13·22	13·31	13·55	13·74
110	Maximum	12·27	13·04	13·37	13·58	13·61	13·66	13·87	13·89
	Minimum	11·42	12·61	13·08	13·21	13·32	13·31	13·56	13·75
	Average	11·86	12·83	13·20	13·39	13·45	13·51	13·78	13·84
120	Maximum	13·13	13·44	13·77	13·81	13·94	14·00	14·18	14·18
	Minimum	12·44	13·06	13·45	13·61	13·70	13·80	14·03	14·03
	Average	12·95	13·27	13·61	13·73	13·81	13·92	14·13	14·11
130	Maximum	13·28	13·85	14·02	14·15	14·21	14·28	14·44	14·62
	Minimum	12·48	13·49	13·80	13·93	14·03	14·11	14·28	14·35
	Average	12·94	13·69	13·90	14·06	14·13	14·22	14·37	14·50
140	Maximum	13·59	14·13	14·28	14·46	14·47	14·60	14·92	15·09
	Minimum	13·45	14·02	14·09	14·36	14·42	14·54	14·79	14·92
	Average	13·52	14·07	14·20	14·42	14·45	14·57	14·87	15·02

Table V. *Showing maximum, minimum and average values of each twelve replicate determinations of moisture content at each temperature for each period of heating for flour.*

Temp. (° C.)		Period of heating (hours) and moisture content (%) 1	2	3	4	5	6	12	14
90	Maximum	13·35	13·93	14·21	14·28	14·30	14·32	14·42	14·42
	Minimum	11·95	13·82	14·07	14·18	14·22	14·20	14·30	14·22
	Average	12·70	13·87	14·13	14·22	14·27	14·26	14·36	14·33
95	Maximum	14·67	14·27	14·49	14·54	14·60	14·67	14·74	14·63
	Minimum	12·09	13·61	14·03	14·23	14·31	14·42	14·19	14·28
	Average	13·25	13·93	14·25	14·42	14·47	14·53	14·43	14·42
100	Maximum	13·85	14·45	14·68	14·63	14·66	14·71	14·77	14·97
	Minimum	12·57	14·12	14·14	14·39	14·32	14·45	14·54	14·63
	Average	13·30	14·35	14·51	14·51	14·52	14·62	14·68	14·71
105	Maximum	13·83	14·71	14·77	14·79	14·83	14·86	14·77	14·91
	Minimum	12·46	13·82	14·45	14·52	14·60	14·57	14·58	14·78
	Average	13·49	14·39	14·66	14·68	14·74	14·71	14·70	14·84
110	Maximum	14·27	14·83	15·20	14·82	14·88	14·97	14·84	14·95
	Minimum	12·96	14·51	14·68	14·72	14·74	14·67	14·69	14·87
	Average	13·83	14·69	14·80	14·77	14·81	14·81	14·80	14·91
120	Maximum	15·06	15·08	15·10	15·16	15·16	15·18	15·23	15·21
	Minimum	14·67	14·80	14·80	14·87	14·97	14·94	15·01	15·01
	Average	14·81	14·91	14·97	15·07	15·07	15·05	15·11	15·09
130	Maximum	15·15	15·24	15·29	15·29	15·33	15·35	15·36	15·45
	Minimum	14·71	14·95	15·04	15·08	15·15	15·05	15·24	15·22
	Average	14·93	15·13	15·18	15·18	15·27	15·24	15·30	15·34
140	Maximum	15·33	15·40	15·36	15·47	15·46	15·57	15·52	15·65
	Minimum	15·28	15·33	15·34	15·47	15·45	15·55	15·52	15·65
	Average	15·31	15·37	15·35	15·47	15·46	15·56	15·52	15·65

Note to Tables IV and V. The values for 90° represent two series only, one on oven *A* and one on oven *B* (*i.e.* six determinations) and those for 140° one series on oven *B* only. Owing to shortage of material the values for flour at 140° were obtained using duplicate samples only of 2 gm. each. Some of the values for flour at 90° were also obtained on 2 gm. samples.

The original sample of wheat was exhausted before the series was completed. A fresh sample of the same lot of wheat was obtained, similar in all respects to the first, except that careful check determinations at 110° showed it to be 0·08 per cent. lower in moisture content. The series at 90°, 95° and 140° were carried out on this fresh sample, those at 100°, 110°, 115°, 120° and 130° having been completed on the original sample.

closely similar, varying between 14·45 and 14·86 per cent.; similarly the 59 samples heated for 3, 4, 5, 6 and 12 hours at 110° gave closely similar results which varied between 14·67 and 15·20 per cent.; the 69 samples heated for 3, 4, 5, 6, 12 and 14 hours at 120° gave concordant results between 14·87 and 15·23 per cent.; and the 36 samples heated for 5, 6 and 12 hours at 130° varied from 15·05 to 15·36 per cent. Each of these four sets of virtual replicates when plotted as a frequency polygon with moisture intervals of 0·05 per cent. gave reasonably symmetrical

distribution about a mode as shown in Fig. 5. The modes were in close agreement with the means: thus,

$T = 100°$ and $105°$	Mean of 89 samples = 14·69 per cent., mode = 14·70
$T = 110°$	Mean of 59 samples = 14·80 per cent., mode = 14·795
$T = 120°$	Mean of 69 samples = 15·08 per cent., mode = 15·10
$T = 130°$	Mean of 36 samples = 15·27 per cent., mode = 15·285

This regular distribution and close agreement between modes and means suggests that each of the flour sets contains a sufficient number of determinations to justify an estimation of probable errors of single determinations (PE_s) of moisture contents. The probable errors were calculated for each group by means of the formula

$$PE_s = 0{\cdot}6745 \sqrt{\frac{\Sigma d^2}{n-1}}$$

in which Σd^2 = the sum of the squares of the deviations of the individual results in each group from the mean of each group and n = the number of results in each group.

The probable error of single determinations so calculated were as follows:

$T = 100°$, 6–12 hours' heating $T = 105°$, 3–12 „ „	$PE_s = 0{\cdot}054$ %
$T = 110°$, 3–12 „ „	$PE_s = 0{\cdot}048$ %
$T = 120°$, 3–14 „ „	$PE_s = 0{\cdot}054$ %
$T = 130°$, 5–12 „ „	$PE_s = 0{\cdot}041$ %

The 31 replicate samples dealt with (5 hours' heating in electric oven at 110°) on May 5 (Fig. 1) gave $PE_s = 0{\cdot}032$, while the 66 replicate samples dealt with at 110° between March 10 and May 2 (Table II) gave $PE_s = 0{\cdot}050$.

It appears therefore that even when the determinations of moisture content are spread over as long a period as 8 weeks (provided of course the material is stored under reasonably air-tight conditions) the probable error of a single determination should not exceed 0·05 and may be actually less than this. As the determination of moisture (or of dry matter) by means of oven drying is not an operation of any scientific precision a PE_s of 0·05 is satisfactorily low. This value applies to the results obtained by the writers using their particular technique and type of oven; we have no evidence as to the degree of reliability of determinations carried out with other types of electric oven or different techniques.

In Fig. 6 the flour curves for 100° to 140° have been re-drawn in the light of the information yielded by the PE_s's. These curves are simpler but quite as accurate as those given in Fig. 4 and it will be

noticed that the following portions form a series of parallel straight lines:

100°	6 to 14 hours	14·70 %
105°	3 to 12 hours	14·70 %
110°	3 to 12 hours	15·10 %
120°	4 to 14 hours	14·80 %
130°	5 to 12 hours	15·25 %
140°	6 to 12 hours	15·50 %

It is also worthy of note that 1 hour at 120° gives the same result (14·80 per cent.) as 3 to 12 hours' heating at 110°.

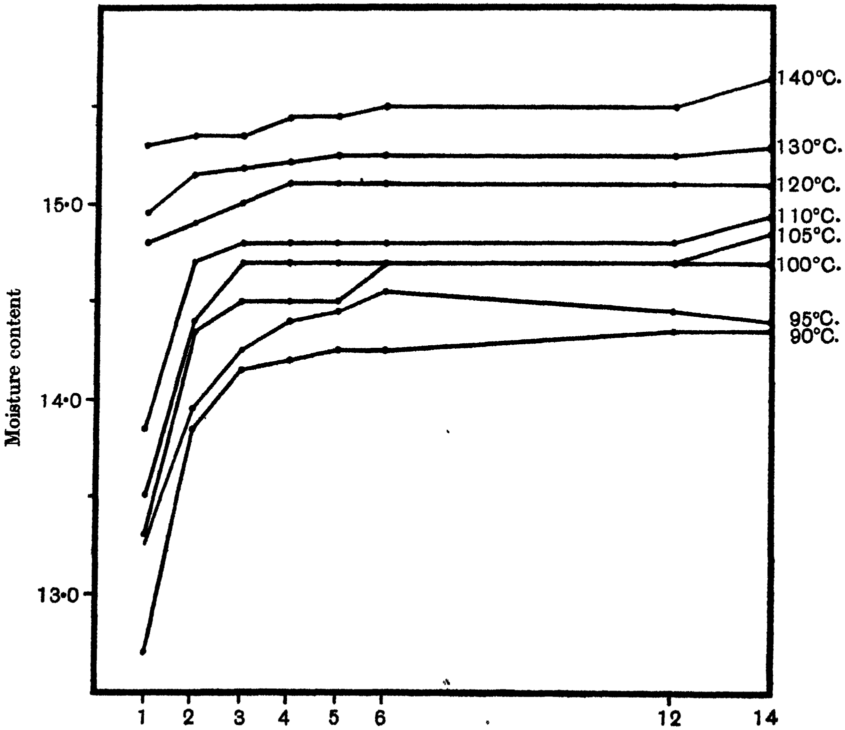


Fig. 6. Apparent moisture content of a sample of flour as determined at different temperatures and with different periods of heating (electric oven). (These curves have been "smoothed" in the light of information yielded by the PE_s's.)

One curious fact that emerged was that at 105° and at 110°, after the samples had remained at constant weight for 9 hours (*i.e.* from 3 to 12 hours' treatment) a further loss of 0·15 to 0·18 per cent. occurred between 12 and 14 hours. This loss did not occur at 100°, nor at 120°,

and was not significant at 130°. It will be of interest to see whether further work confirms this point.

Some millers employ 1 hour's heating at 140° for both wheat and flour. Fig. 6 shows that with the flour used in these experiments 1 hour at 140° gave 0·5 per cent. more moisture than 3 to 12 hours at 110°. For wheat (see Fig. 3) 1 hour at 140° gave the same result as 6 hours at 110° or 12 hours at 100°.

The wheat results (Table IV) were less satisfactory than those for flour. At all temperatures there was a fairly regular increase in apparent moisture content with increasing time of heating although the increase between 12 and 14 hours at 110° and 120° was only just appreciable. It was not therefore possible to calculate PE_s directly in this case. An examination of Table IV reveals that the range of variations in each group of 12 replicates was substantially similar for both ground wheat and flour. It seems not unlikely therefore that the wheat results have a similar degree of reliability to those for flour.

Table VI. *Mean values of moisture contents of No. 1 N. Manitoba, English and Durum wheats (ground) heated for different periods at* 110° *and* 120° C.

Period of heating (hours)	Apparent moisture contents			
	Manitoba wheat 110°	Manitoba wheat 120°	English 110°	Durum 110°
1	—	—	18·77	19·44
2	—	—	19·21	20·12
3	—	—	19·42	20·55
4	—	—	19·41	20·65
5	13·83	—	19·62	20·83
6	—	—	19·57	20·74
10	14·04	14·27	—	—
12	—	—	19·54	20·99
14	—	—	19·63	20·95
15	14·07	14·30	—	—
24	14·19	14·44	—	—
48	14·06	14·55	19·42	21·13

This part of the work was extended so as to include periods of heating up to 48 hours using (*a*) another sample of the same bulk of No. 1 N. Manitoba wheat of practically identical moisture content, (*b*) English, and (*c*) moistened Durum wheat. In each case six replicates were heated for each of the periods and the temperatures employed were 110° with English and Durum and 110° and 120° with Manitoba wheat. All the replicates were closely concordant (the extreme range of variation in any one set of six being 0·12 per cent.) and the mean results are given in Table VI. It will be seen that the Manitoba sample showed no

significant change between 10 and 48 hours' heating at 110° but at 120° the change of 0·25 per cent. between 15 and 48 hours was probably just significant. The Durum wheat showed no significant change at 110° between 12 and 48 hours and the English none between 5 and 14 hours. The barely significant fall of 0·21 per cent. between 14 and 48 hours may be due to slight oxidation of fat or may be accidental.

The following tentative suggestions are put forward:

It is desirable, although not essential, that the same temperature be used for both wheat and flour. It is suggested that a convenient temperature is 110°, and that the period of heating should be any period, convenient to the miller, between 3 and 12 hours for flour and from 12 to 15 hours for ground wheat. Since speed of working is commonly an important consideration in a mill, the period of heating can be greatly reduced by working at 120° instead of at 110°: 1 hour at 120° for flour and 4 hours at 120° for wheat should give results identical with those obtained by the longer periods at 110°. A further saving in time could be effected if two electric ovens were used simultaneously at different temperatures, one for flour and one for wheat. One hour's heating at 120° for flour and 1½ hours' heating at 140° for wheat should give results identical with those obtained by the usual long heating at 110°.

While this work was in progress (in 1925) a sample of the flour used was placed in thin layers in a desiccator (not evacuated) over concentrated sulphuric acid and left undisturbed for 2½ years. The desiccator was then opened, triplicate samples of the dried flour were transferred as rapidly as possible to containers, and the moisture contents determined in the manner recommended by heating for 1 hour at 120°. The observed moisture contents were as follows: 0·0009, 0·0013 and 0·0013 per cent.

This close agreement between the moisture contents as determined by electric oven drying at 120° (for 1 hour) or 110° (for 3 or more hours) and by prolonged drying over concentrated sulphuric acid suggests that such results, while markedly higher than those obtained by water oven drying, are still low as it is highly improbable that complete desiccation of flour can be obtained by drying, however prolonged, over sulphuric acid (cf. also Nelson and Hulett (5)).

Effect of Cooling in Desiccator.

In a trial carried out in the writers' laboratory, nine similar 5-gram samples of flour were heated at 110° for 5 hours, cooled (with covers on) 20 minutes in a sulphuric acid desiccator, and weighed. They were found to have substantially the same moisture content. Then three were

allowed to stand overnight in a desiccator containing sulphuric acid, three in one containing calcium carbide and the remaining three in one containing calcium chloride (again with covers on in all cases). Next morning they were weighed again.

The following are the averages of the three results in each case showing the pick-up of moisture in the desiccator expressed as per cent. of the original weight of the samples.

Calcium chloride	0·0030
Calcium carbide	0·0009
Sulphuric acid	0·0010

These figures show that the type of desiccating agent is of no importance if containers remain covered during cooling. Calcium carbide is however probably the most convenient for routine work in mills where "moisture testing" is often carried out by unskilled workers.

EFFECT OF SIZE OF SAMPLE.

Some inconclusive work on the effect of size of sample on the apparent moisture content was done by Leatherock (4) and by the American Committee (1).

Table VII. *Influence of size of sample on determination of moisture content of flour* (5 *hours heating at* 110°).

Approximate size of sample (gm.)	Moisture content (%)	
	Replicate values	Mean values
2	18·22; 18·19; 18·14—top shelf	18·18
5	18·27; 18·29; 18·23—top shelf	18·26
5	18·25; 18·23; 18·18—bottom shelf	18·22
10	18·23; 18·19; 18·07—top shelf	18·16
15	18·28; 18·24; 18·24—top shelf	18·25

Our results are given in Table VII. Triplicate determinations were carried out on the same flour sample (5 hours' heating at 110°) using 2, 10 and 15 gm. samples and two sets of triplicates on 5 gm. samples (one set on each shelf). The extreme difference between the mean values was 0·10 per cent. and that between individual determinations was only 0·22 per cent.

From these results it appears that size of sample within the limits studied is not an important factor in the determination of moisture content.

Method Recommended for Determination of Moisture in Flour and other Cereal Products.

Hearson's electric ovens, fitted with metal thermostat, have been used in the work reported in this paper and have proved satisfactory. The balance used was by Oertling, with chainomatic attachment. This latter accessory increases the first cost of the instrument, but enables much time to be saved when large numbers of weighings have to be done.

The aluminium containers used in these laboratories are not the usual ones sold at 2*s*. each by most laboratory furnishers, but ordinary aluminium ointment tins as used by pharmacists. These are very satisfactory and can be purchased in dozens at $2\frac{1}{2}d.$ to 3*d*. each tin. The most convenient size is $2\frac{1}{2}$ in. diam. by $\frac{3}{4}$ in. deep. The lids are close-fitting and may be perforated and fitted with small electric terminals to serve as handles.

The containers should be dry-cleaned, as soon as possible after use, with a stiff-bristled brush and kept in a dust-tight drawer when not in use. Weighings throughout need only be made to the nearest milligram.

Thoroughly representative samples of the stocks to be tested are taken and immediately placed in glass-stoppered bottles. When the test is to be made the whole of the sample is poured on a large sheet of smooth paper, thoroughly and quickly mixed, and, in the case of flour, semolina, middlings, bran, etc., duplicate samples of roughly 5 gm. are used. In the case of wheat, the coffee mill is first "washed out" by running through and rejecting a few grams, after which about 15 gm. of the sample are *quickly* ground and sampled in duplicate lots of roughly 5 gm. each into the aluminium containers.

The containers should be covered immediately after receiving their samples of wheat, flour, etc., and weighed at once. They are then heated as follows: *at* 110° *for any convenient period of from* 3 *to* 12 *hours for flour and* 12 *to* 15 *for wheat;* or *at* 120°, 1 *hour for flour and* 4 *hours for wheat;* or 1 *hour at* 120° *for flour and* $1\frac{1}{2}$ *hours at* 140° *for wheat* (in this case two ovens are necessary).

Whilst actually in the oven the containers must be uncovered; the lids may be conveniently left resting half-over their respective containers. As far as possible all samples to be heated for a given time should be placed in the oven together. *The oven should not be opened until it is time for all the samples to be removed**, when the containers should be

* This arrangement is not always practicable under routine conditions at busy times, but that it is desirable has been shown in the text and it should be adhered to whenever possible. When higher temperatures and shorter periods are used disturbance produced by opening the oven is particularly serious.

quickly covered and placed in a desiccator for about 20 minutes before weighing.

Summary.

The nature of the problem of moisture determinations on materials such as flour and wheat is discussed shortly. It is not possible to obtain by over drying true values for moisture contents. What is sought is a convenient and reliable procedure giving strictly reproducible figures possessing full comparative value. This was the object of the work described, the main lines of which should be applicable to agricultural products of many kinds.

The electrically heated air oven is the most convenient and suitable instrument for routine purposes, and comparative results show that it allows of far more reliable work than the water oven.

Determinations of apparent moisture content have been made on a sample of wheat flour in electric ovens at temperatures ranging from 90° to 140° C. and for periods of heating ranging from 1 to 14 hours, the technique and number of determinations (about 400 altogether) being such that the results were suitable for statistical examination. The probable errors of single determinations were calculated for several sets of results and did not exceed 0·05 per cent. The results given show that at several temperatures, variation in time of heating over a considerable range does not affect the values obtained. In the light of these results it was possible to assess the reliability, as well as the convenience, of various possible procedures.

Similar experimental work was carried out on ground wheat. The results differed from those for flour in that over the ranges studied at all temperatures the figures obtained increased steadily but at diminishing rates with increasing time of heating up to about 12 hours.

The effects of position of containers in the type of electric oven used and of size of sample taken are shown to be negligible, but 5-gram grab samples are recommended as most convenient.

Calcium carbide is shown to be as efficient a desiccating agent as sulphuric acid, and it is more suitable for routine work in mills.

A standard method for moisture determination is recommended.

Many of the moisture determinations carried out in this investigation were performed by Mr T. Colborne of whose careful work the writers desire to express acknowledgment.

REFERENCES.

(1) Committee of Amer. Assoc. of Cereal Chemists. *Cer. Chem.* **1** (1924), p. 190.

(2) Bidwell, G. L. and Sterling, W. F. (1925). *Ind. and Eng. Chem.* **17**, 147.

(3) Coleman, D. A. and Boerner, E. G. *U.S. Dept. Agr. Bul.* 1375 (1926); and also *U.S. Dept. Agr. Bur. Agr. Economics, Grain Division:* Specification, etc. for Official Moisture Tester (1922–3).

(4) Leatherock, L. E. (1922). *J. Amer. Assoc. Cer. Chem.* **7**, 102.

(5) Nelson, A. and Hulett, G. A. (1920). *Ind. and Eng. Chem.* **12**, 40.

(6) Shutt, F. T. and Moloney, T. (1917). *Trans. Roy. Soc. Canada*, Series III, Sec. III, **2**, 101.

(7) Smith, E. R. and Mitchell, L. C. (1925). *Ind. and Eng. Chem.* **17**, 180.

(8) Snyder, H. and Sullivan, Betty (1924). *Ind. and Eng. Chem.* **16**, 741.

(9) Spencer, G. C. (1925). *J. Assoc. Off. Agr. Chem.* **8**, 301.

(*Received June 2nd*, 1928.)

THE CAPILLARY PULL OF AN IDEAL SOIL.

By FELIX E. HACKETT, Ph.D. and JOHN S. STRETTAN, M.Sc.
(*University College, Dublin.*)

(With Four Text-figures.)

§ 1. Introduction.

The problem of capillarity in soils has been generally attacked from the theoretical side by the consideration of ideal soils consisting of uniform spherical particles. Even after the irregularities of size and shape have been eliminated the packing of the particles remains an uncontrollable factor. Only the cases of cubical and close packing are completely amenable to theoretical treatment, though it is difficult to realise either experimentally. More usually we have an intermediate condition. In the work described below, the capillary pull for this common but indefinite state of packing has been determined directly. By measuring the pull sustainable by liquid films in apertures formed by four spheres in contact, some information has been obtained on the kind of apertures existent in ordinary packing. A method of calculating the pull for these curvilinear openings is given which shows satisfactory agreement with experiment.

The analysis of Slichter (1) of the properties of an assemblage of uniform spheres in relation to the flow of air and water has formed the foundation of many subsequent investigations. The agreement of his expression for the permeability of an ideal soil has been tested by King (1) and subsequently by Green and Ampt (2) who investigated the permeability of very small beads for different kinds of packing.

These experiments gave values 50 per cent. to 85 per cent. greater than the calculated values; for soils and sands they found a closer agreement. These results have therefore given favourable support to Slichter's method of treating the pore space as a bundle of capillary tubes with an approximately triangular cross-section. In drawing attention to the very diverse views which had been expressed as to the height H to which water can rise under the action of capillary forces, Keen (3) used this conception of a triangular tube to calculate H. He found $Hg\rho = 19{\cdot}8T/2a$, where T is the surface tension, ρ the density of the liquid, a the radius of the particle. The term $Hg\rho$ may be termed the

pressure deficiency P since it is the fall in pressure in passing from air through the liquid meniscus. It is convenient to use the symbol K for the numerical constant, and it will be used, for brevity, as a capillary coefficient throughout this paper, so we write in general

$$P = Hg\rho = KT/2a \qquad \text{......(1).}$$

In a series of experiments on the ascent of oils through sands Hackett (4) found that the average value of K was 7·84. The discrepancy between this figure and the value 19·8 deduced by Keen led to the work described here.

During its progress papers by Haines (5) and Fisher (6) have appeared dealing principally with the cohesion arising out of the capillary forces in an ideal soil. In a later paper Haines (7) has considered also the relation between the capillary forces and the movements of the liquid when it almost fills the interstices of the ideal soil which has a close connection with the subject matter of this paper.

§ 2. Determination of K for Small Glass Spheres.

Following Green and Ampt, small glass spheres, fairly uniform in size, were obtained by elutriating in accordance with the method described by them, the "hoar frost" of commerce. The capillary height was determined by measuring directly the hydrostatic pull which a liquid film, filling the spaces between the glass spheres, can sustain. This principle has been used by other observers and is readily applied in the apparatus shown in Fig. 1. A U-tube is provided with a stopcock near the bend for the outflow of liquid. One arm is in two portions, connected by a ground-glass joint. The upper tube is constricted so that it supports a piece of wire gauze mounted on a brass ring on which the glass spheres rest. The apparatus is filled with liquid and the spheres added with constant tapping, until they accumulate to a height of 1 or 2 cm. It may be noted that the packing is done in liquid and not in air. Otherwise the rush of air through the spheres on introducing the liquid would disturb their piling and give irregular results.

When the stopcock is opened, the liquid descends in the open tube until there is a difference in level corresponding to the capillary height. The liquid now descends at an equal rate in both tubes until the liquid film has reached the bottom of the column of glass beads and breaks. Air enters through the column and the meniscus in the open tube rises. This point of reversal can be accurately observed. The difference of level between this point and the base of the bead column is taken as equal to

the capillary height (H). As the liquid runs out, we have a continual breaking down and reforming of liquid surfaces. If this goes on too rapidly, we do not approach static conditions. Observations taken for rates of flow less than one drop in five seconds were considered reliable.

The effect of contamination was avoided by using common liquids of low surface tension: paraffin, benzene, turpentine and methylated spirit. The measurements with benzene had the greatest precision and may be mentioned in detail. The value of $T/g\rho$ for the benzene used in these observations was found to be $33{\cdot}8 \times 10^{-3}$ at 16° C. This is closely in accord with the value given for chemically pure benzene by Richards (8). In view of the importance of packing, an approximate determination of the mean pore space was made by measuring the capacity per cm. of the glass tube above the brass gauze, and weighing the quantity of glass spheres used. Their density was 2·915 gm./cm.^{3}.

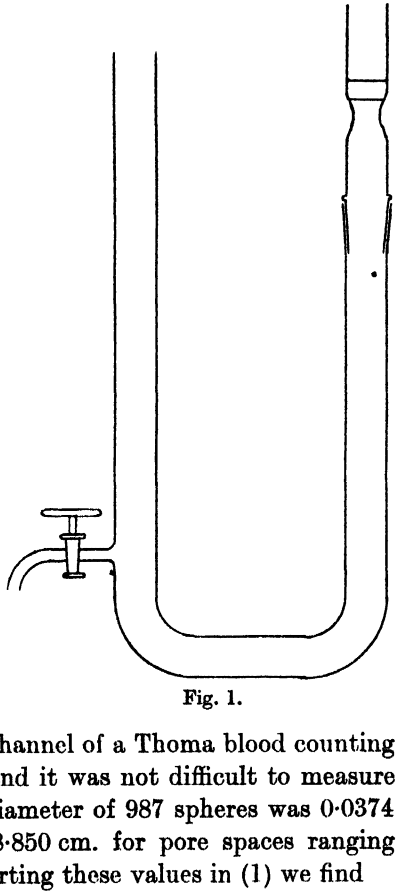


Fig. 1.

The diameter of the beads was measured by a microscope, with a micrometer eyepiece calibrated by a Leitz micrometer scale. The circular channel of a Thoma blood counting cell formed a convenient receptacle, and it was not difficult to measure groups of 100 at a time. The mean diameter of 987 spheres was 0·0374 cm. The mean capillary height was 8·850 cm. for pore spaces ranging from 36 per cent. to 40 per cent. Inserting these values in (1) we find

$$K = 9{\cdot}76.$$

The principal error in this measurement lies in the determination of the mean diameter of the glass beads. The elutriation did not effect a complete sorting and errors of 5 per cent. or more were possible from random sampling as shown below:

No. of beads	**104**	**135**	**208**	**126**	**86**	**167**	**161**
Mean diameter in mm.	**·358**	**·396**	**·382**	**·393**	**·384**	**·354**	**·355**

As the total quantity of beads used in the experiments with benzene was not more than 4 gm., it is believed that the mean diameter of 987 represents a fair sample.

Similar measurements summarised in Table I were carried out with other liquids, but these were not of the same order of precision as they involved the use of 120 gm. of glass beads, whose mean diameter was found to be 0·037 cm. from 1347 observations.

Table I.

Nature of liquid	K
Turpentine	9·16
Methylated spirit	9·52
Paraffin oil	9·90
Mean	9·53

§ 3. Determination of K for Three or Four Spheres in Contact.

The next step was to devise a method of calculating K and to explain the above results. In any assemblage of spheres, we have groups in close or cubical packing. Some distortion will almost certainly exist. If we denote by 2α the angle between the lines joining the centres of two spheres to the centre of a third in contact with both, α varies from 45° for cubical packing to 30° for close packing. Clearly the proper procedure was to determine the capillary pull sustainable by the films between spheres in all forms of contact, for values of α ranging from 45° to 30°. The method described in § 2 was found to be applicable, with some small alterations, to small steel balls of $\frac{1}{8}$ in. and $\frac{3}{8}$ in. diameter used in ball-bearings. One limb is closed by a brass plate, drilled to support three or four spheres making any desired angle of contact. The apparatus is filled with liquid so that a film is formed between the spheres. On allowing the liquid to flow out slowly in drops, the meniscus in the open arm descends to some point until the liquid film can no longer sustain the difference in pressure between the atmosphere and that just beneath the surface. This maximum pressure ($Hg\rho$) measures the capillary pull due to the film in the opening between the spheres. It is easily determined from the difference of level (X) between the meniscus in the open limb at the moment of break and the top of the spheres taking note of some few corrections discussed below.

The small crevices which exist between the brass plate and either the spheres or the glass tube are sealed by liquid films during the experiment, since they are much smaller than the openings between the spheres, and consequently are capable of supporting a greater pressure. The observed

height (X) is the difference in level between the top of the spheres and the level of the meniscus in the open column. To find H we have to subtract a the radius of the spheres, R the radius of curvature of the

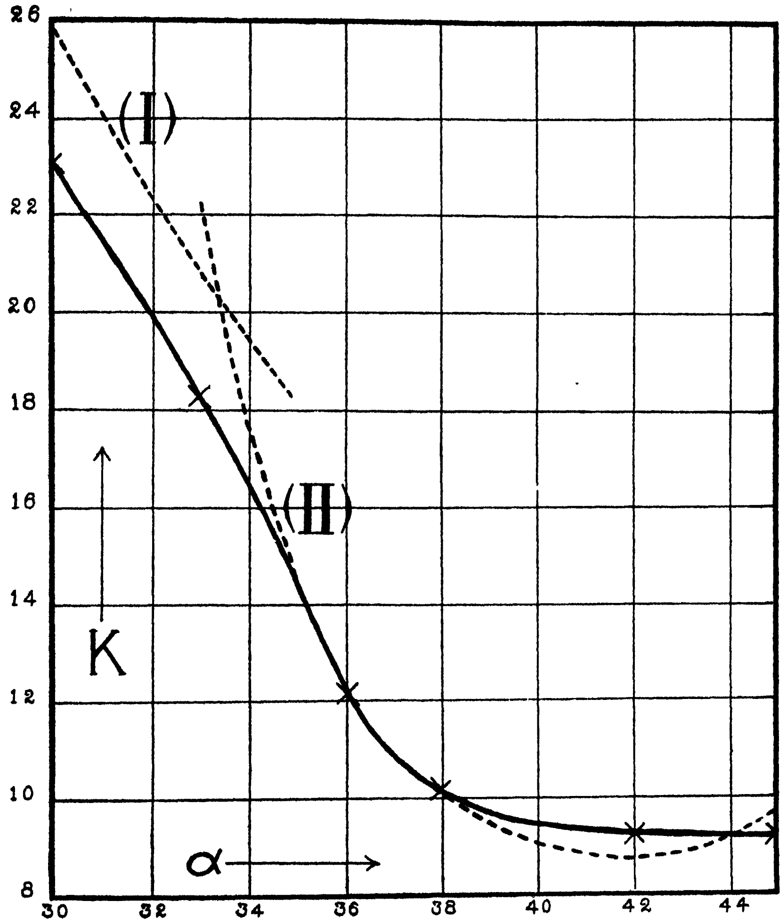


Fig. 2.

liquid film, and add h the capillary elevation of the meniscus in the open tube. The radius of curvature in the liquid film is small and may be calculated approximately from the observed height (X) by writing

$$Xg\rho \fallingdotseq 2T/R.$$

The capillary elevation in the wide tube may be readily obtained from tables given by Sugden (9). For benzene in a tube of radius 0·39 cm.

which was used throughout most of the work we find the capillary elevation to be 0·094 cm. We can therefore write

$$H = X - a - R + 0{\cdot}094,$$

and find K by (1). The empirical curve for K is shown in Fig. 2. The angle of packing (α) was determined by measuring the distance between the centres of the spheres along the short and long axes of the curvilinear aperture.

§ 4. Theoretical Calculation of K.

These observations form a basis for comparison with theory. For this purpose we require some method of calculating the radius of curvature R of the film at its lowest point, and hence deducing K. This calculation from the laws of surface tension would be an intractable problem. A simple solution of an empirical character has been found. Since the contact angle of benzene with metals is zero we may imagine in the simple cases of close or cubical packing that a spherical surface of radius R, coinciding with the film at its lowest point, touches the three or four supporting spheres along their horizontal diametral plane. This spherical surface will follow closely the contour of the liquid film in any vertical section containing the lowest point and the centre of one of the spheres. As will be seen below, this picture of the film surface, while not in absolute agreement with the observations, proves an excellent approximation and furnishes a method of attack on a difficult problem.

Case I. *Cubical packing.* It is easily seen that a hemisphere touching four spheres of radius a in a plane passing through their four centres has a radius R given by

$$R + a = a\sqrt{2}.$$

Substituting the formula $2T/R = H\rho g$ in (1) and using this value of R we get

$$K = \frac{2aH\rho g}{T} = \frac{4a}{R} = 9{\cdot}66.$$

Case II. *Close Packing.* Haines (7) is of opinion that "a concave film covering the entry to a waist (the smallest interstice in closest packing) might have a pressure deficiency approaching the value $12{\cdot}8T/a$." The basis of this estimate rests on the same assumption as that adopted here: the curvature of the surface film is that of a hemisphere touching three spheres of radius a in this packing in the plane containing their centres. From a figure we easily find that R is given by

$$\tfrac{2}{3}\sqrt{3}\,.\,a = R + a,$$

from which we get $$K = \frac{4a}{R} = 25{\cdot}86.$$

The comparison of these theoretical values of K with observation is shown in Table II. The liquid used was benzene and the value of $T/g\rho$ determined at the time of observation was $33{\cdot}4 \times 10^{-3}$.

Table II.

	Cubical packing	Close packing	
Height observed (X)	1·108	1·798	2·505
Corrected capillary height (H)	0·962	1·588	2·38
Diameter of spheres (cm.) ...	0·3175	0·48	0·3175
K obs.	9·15	22·8	22·6
K calc.	9·66	25·86	

The close agreement in the experimental values, for spheres of different sizes in close packing, seems to show that the discrepancy between observation and the calculated values is not due to the size of the opening. Under a microscope the liquid surface has almost a puckered appearance. This mode of calculation, therefore, gives only a fair approximation.

The form of the liquid surface for distorted packing is difficult to determine, but it has been considered worth while to endeavour to extend the method given above to obtain the theoretical curve for K, which would help to explain the experimental curve. It has been found necessary to consider two cases.

Case III. *Approximate close packing.* Here we have four spheres in contact so that the plane rhombus formed by joining the centres has an acute angle near 60°. The liquid surface consisting of two depressions each almost surrounded by three spheres and united by a ridge may be assumed, in each depression, to coincide closely with a spherical surface touching the three nearest spheres in their diametral plane. If R is the radius of curvature of the small circle in either depression in Fig. 4, then

$$a = (a + R) \cos \alpha,$$

which gives

$$K = \frac{4a}{R} = \frac{4 \cos \alpha}{1 - \cos \alpha}.$$

The values of K given by the equation are plotted as Curve I in Fig. 2.

Case IV. *Approximate cubical packing.* When the acute angle of the plane rhombus formed by the centres of the spheres is about 80°, the liquid film will evidently have two principal radii of curvature along the short and long axes of the opening.

It seems reasonable to treat the lowest part of the film as approximating to the spheroid touching the spheres in the plane containing

their centres; its axis of revolution is the longer axis of the curvilinear opening which joins the centres of two opposite spheres. In the vertical plane containing this axis, the section is an ellipse having as axes pa and qa. The radius of curvature at the end of qa is p^2a/q, while in the other principal plane, containing the shorter axis of the opening, the

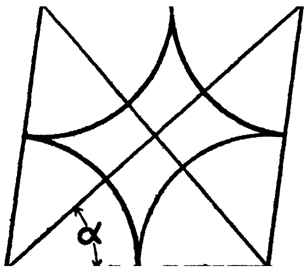


Fig. 3.

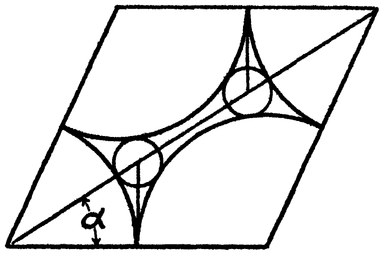


Fig. 4.

section of the film approximates to a circle with a radius qa. We have from Fig. 3

$$p = 2\cos\alpha - 1,$$

$$q = 2\sin\alpha - 1,$$

$$Hg\rho = T\left[\frac{1}{qa} + \frac{q}{p^2a}\right],$$

giving

$$K = \frac{2aH}{T/g\rho} = \frac{2}{q}\left[1 + \frac{q^2}{p^2}\right].$$

The values of K obtained from these equations are plotted as Curve II in Fig. 2. They follow the general run of the experimental values from $\alpha = 45°$ to $\alpha = 35°$.

This mode of calculation is clearly equivalent to asserting that the equivalent capillary tube is the circular or elliptic cylinder which touches the spheres forming the aperture. Such a cylinder exerts a capillary pull differing not more than 5 per cent. at any point for approximate cubical packing, but is about 10 per cent. less for close packing.

§ 5. Discussion.

It is quite evident that just as the strength of a chain is its weakest link, so the strength of a liquid film spread over spheres arranged closely together depends on the largest apertures amongst them, due to contacts of four and occasionally even of five spheres. The film gives way easily in the exceptionally large apertures and descends until it meets an

average sized aperture in which it becomes stable. The actual details of the descent of a liquid surface through 3 cm. of glass spheres, described in § 2, are instructive. The glass spheres have nearly the same index of refraction as benzene, so the granular medium when filled with liquid is almost translucent and the position of the liquid can be easily observed even in the interior of the column. As the liquid slowly descended in the open limb, the hydrostatic pull slowly increased. The film gave way at one point under a pressure of 8·2 cm. and descended then in a sort of tongue-like projection. On the increase of hydrostatic pull the film gave way at other points and became nearly a horizontal plane at a pressure of 8·5 cm. It then fell uniformly as the pressure difference increased to 8·7 cm. The increasing strain then discovered another channel down which a tongue descended until it reached a constriction at which the liquid at its tip was in equilibrium for a pressure of 8·82 cm. Meanwhile the main part of the free surface remained behind sustaining a pressure of 9·38 cm. At this stage the tip of the tongue reached almost to the base of the column. It was unstable. The flow of liquid was extremely slow. A slight disturbance now broke the film for a pressure of 8·867 cm.

The successive values of the hydrostatic pull H are correlated in Table III with K and the corresponding value of α the angle of packing taken from the empirical curve in Fig. 2. In the last row the ratio of the breadth to the length of the aperture along the lines joining the centres of opposite spheres is also given.

Table III.

H	8·2	8·5	8·7	8·85	8·867	9·38
K	9·15	9·45	9·60	9·70	9·80	10·4
α	45°–42°	40°	—	—	39°	38°
$\frac{\text{Breadth}}{\text{Length}}$ aperture	1–0·7	·53	—	—	·46	·40

In this experiment the column was formed by adding small quantities of the glass beads at a time while carefully tapping the tube. The pore-space was 36·5 per cent. The breaking point occurred, however, about the same point for packing up to 40 per cent. as already mentioned in § 2.

The experiments in this paper show that the capillary pull for spheres of radius a or pressure deficiency arranged in common packing is given by the equation

$$Hg\rho = 9{\cdot}5T/2a = 4{\cdot}75T/a.$$

It is true that the value obtained in the precise experiments with benzene

is a little higher, but taking all the experimental data, including the observed graph of Fig. 2, 4·75 seems a reasonably weighted mean.

Haines (7) has studied the pressure deficiency in a granular medium by observing the pressure of the liquid in a porous pot surrounded by small spheres saturated or partially saturated by the liquid. As evaporation goes on, the liquid meniscus draws into the pores and the pressure deficiency rises to the entry value. Haines used a considerable number of materials consisting of approximately spherical grains and assessed the average value of his observations at $6T/a$, as the pressure deficiency at entry for pore spaces ranging about 37 or 38 per cent. This he considers rather low "about one-half that which has been calculated as a maximum for the ideal case. But it is to be remembered that that value was an upper limit and such packing was never attained in the real case.... The values of the surface tension taken are those for pure liquids and it is probable that contamination caused lower values to rule in most of the experiments, so that the factor 6 errs on the low side."

On the contrary, it is probably in error on the high side, for in the experiments described in this paper in which the lower average value of $4{\cdot}75T/a$ was obtained, care was taken to avoid contamination and the value of the surface tension was determined by the same apparatus, using a modification of Jaeger's method. In addition the front of the liquid must adjust itself so that the change of pressure passing from atmosphere to the liquid is the same at the same horizontal level. We shall get an equilibrium corresponding to the average value of K which will depend on the average size of the aperture and the variation of K with the angle of packing. The slow change of K from 9 to 10 between the angles of 38° and 45° favours the domination of values of K between these limits in any packing which does not approach close packing. We should expect then that the average value of the pressure deficiency should be between $4{\cdot}5T/a$ and $5T/a$ as found directly, in spite of variations of the pore-space between 36 and 40 per cent. It is not possible to make any definite assertion with respect to the packing angle but it is evident that apertures of closest packing must play a smaller part than is usually assigned to them in determining the capillary rise in an ideal soil.

SUMMARY.

1. The capillary pull of an ideal soil has been determined by measuring the maximum hydrostatic pressure (H) sustainable by a liquid surface formed amongst an assemblage of uniform spheres of mean diameter 0·0374 cm. ($2a$). It has been found that using liquids of low surface

tension like benzene to avoid contamination, the constant K in the equation $Hg\rho = KT/2a$ has the weighted value 9·5.

2. Values of K for single apertures between three and four spheres in contact have been determined, using steel spheres of a diameter $\frac{1}{8}$ in. and benzene. It is found that K does not vary rapidly for four spheres and has a value between 9 and 10 for apertures in which the ratio of breadth to length varies between 1·0 and 0·4.

3. The equivalent capillary tube is the circular or elliptic cylinder touching the spheres forming the aperture. This assumption gives values of K in fair agreement with observation.

4. The value of K is practically independent of variations of pore-space ranging from 36 per cent. to 40 per cent. such as usually occur in ordinary packing.

REFERENCES.

(1) KING and SLICHTER. *19th Ann. Rep. U.S. Geol. Survey*, 1899, p. 172.
(2) GREEN and AMPT (1912). *J. Agric. Sci.* **5**, 396.
(3) KEEN, B. A. (1919). *J. Agric. Sci.* **9**, 396–399.
(4) HACKETT, F. E. (1922). *Trans. Faraday Soc.* **17**, Pt 2, p. 260.
(5) HAINES, W. B. (1925). *J. Agric. Sci.* **15**, 529.
(6) FISHER, R. A. (1926). *J. Agric. Sci.* **16**, 492.
(7) HAINES, W. B. (1927). *J. Agric. Sci.* **17**, 264.
(8) RICHARDS, SPEYER and CARVER (May, 1924). *J. Amer. Chem. Soc.*
(9) SUGDEN (1921). *Trans. Chem. Soc.* **119**, ii.

(*Received June 2nd*, 1928.)

THE PROTEINS OF DIFFERENT TYPES OF PEAT SOILS.

By W. L. DAVIES.

(*Faculty of Agriculture and Horticulture, University of Reading.*)

In the accumulation of organic matter during peat-growth, there is an accompanying accumulation of nitrogen, and the ratio of rate of nitrogen metabolism to that of carbon metabolism is less in organic than in normal mineral soils.

Schreiner and Shoring (1910) separated products of protein cleavage from hydrolysed soil organic matter, isolating arginine and histidine in various proportions as well as some organic bases, while André (1902) had found that extraction of soils with normal hydrochloric acid yielded one-seventh of their nitrogen as ammonia. Jodidi (1910) working on various brown peats, extracted 70 per cent. of the nitrogen with dilute acids, 67–75 per cent. of the extractable nitrogen being monamino acids, 20–25 per cent. amides, and the remainder diamino acids. The organic nitrogen substances were found to change little with weathering.

Gerlach and Densch (1913) found that the nitrogen of ammonium salts and nitrates, applied to peaty soils partly entered into insoluble protein combination. Valmari (1914) found that 85–97 per cent. of the nitrogen of peaty and garden soils existed in protein combination. The treatment of such soils with acids and alkalis dissolved out the nitrogen in amino acid combination, it being found much easier to break down the proteins of slightly decomposed peat than those of humified peat.

Bottomley (1917), extracting raw peat with 1 per cent. sodium bicarbonate, found that no nucleic acid could be isolated, but the presence of dinucleotides and purine bases was demonstrated, it being suggested that nucleic acid was split up during peat formation. Walters (1915) found that soils contain a mixture of proteoses and peptones from protein hydrolysis which exist and persist as such for a considerable period, the original protein hydrolysing very slowly.

It is apparent, therefore, that accumulated nitrogen appears in peaty soils in complex protein combination. To examine the nature of these nitrogen compounds further, and to study the effect of reaction of medium in which peat deposition had occurred on the nitrogen distribution in the various peat proteins, was the aim of the present investigation.

For this purpose a number of samples of peaty soils were collected, their description being as follows:

A. Water meadow peaty soil, laid down in and frequently irrigated with calcareous water. From the Trent Valley, Dorsetshire.

B. As *A*, but from a neglected water meadow in the Lambourn Valley, Berkshire.

C. Calcareous tufa peat from the Kennet Valley, Berkshire.

D. Livery peat resting on chalk (wet). Thames Valley.

E. Dry thin acid peat resting on chalk. Lambourn Down, Berkshire.

F. Originally an acid sandy peat but subsequently irrigated by calcareous water in the Trent Valley, Dorsetshire.

G. Dry sandy acid peat from Windsor Forest, Berkshire.

H. Calcareous fen peat from Cambridgeshire.

I. Acid peat from wet basin (carr soil). Carmarthenshire.

K. Dry acid moor peat from Carmarthenshire.

For comparative purposes, the nitrogen of two normal soils in the Southern Province were also investigated. These consisted of:

L. Sour boulder clay grassland from N. Buckinghamshire.

M. Normal arable soil (clay with flints) from Berkshire.

The soils were worked on in the air-dry state after pulverising so as to pass through a 1 mm. sieve. No stones occurred in the peaty soils, but the ordinary coarse samples of *L* and *M* were broken down to pass through a 1 mm. sieve before being worked on. Moisture and loss on ignition were determined in the samples, using the ammonium carbonate method for ensuring all chalk being present as calcium carbonate in the ignited sample. Total nitrogens were determined by the Kjeldahl method and total carbonates by a calcimeter.

The percentage humification of the organic matter was determined by digesting the soils with hot hydrogen peroxide until all effervescence had ceased. (All determinations were carried out in duplicate and sometimes in triplicate.) The results obtained appear as part of Table I.

I. Hydrolysis of the Nitrogen Compounds.

Three methods were used to break up the nitrogen compounds: (*a*) boiling with hydrogen peroxide, (*b*) extracting with constant boiling point hydrochloric acid for 48 hours, and (*c*) extraction with 2·5 per cent. caustic potash by boiling for 48 hours.

(*a*) *Hydrogen peroxide extraction.* This consisted in destroying the humified portion of the organic matter so as to leave the cellular portion

unattacked. The extracts were filtered and made up to standard volume, total nitrogen and ammonia nitrogen being determined in aliquot portions of the total volume. No information was available as to the exact action of hydrogen peroxide on proteins but much of the nitrogen appeared finally as ammonia. The amino acid nitrogen was not completely oxidised to ammonia since there was an appreciable amount of amino acid left which was resistant to oxidation by the reagent. Comparable conditions were observed for all soils and the results obtained were deemed sufficiently accurate for comparative purposes.

(*b*) *Hydrochloric acid extraction.* This was carried out by the standard method of soil extraction for the determination of total plant nutrients present. Large quantities of furfural were given off from each soil during digestion. The extracts were separated by filtration and thorough washing of the residues, afterwards making up to standard volume. Total extracted nitrogen was determined by estimating the nitrogen present in aliquot portions, the unextracted nitrogen being calculated by difference from the total nitrogen content (*v.* Table I).

(*c*) 2·5 *per cent. caustic potash extraction.* In order to obviate the partial destruction of amino acids such as occurs when protein hydrolysates are heated with strong acids in the presence of soluble carbohydrate, 2·5 per cent. caustic potash solution was used for extraction. One part of soil was boiled with ten parts by weight of solution for 48 hours. By this method, all amide (and other volatile base) nitrogen was driven off leaving an extract composed of small amounts of non-volatile bases and potassium amino acid salts. The alkaline extract could not be filtered so it was slightly acidified and 50 c.c. of 5 per cent. calcium chloride solution added to assist the granulation of the gelatinous precipitate. The extract could now be easily filtered. After thorough washing of the precipitate, the filtrate and washings were made up to standard volume, and total nitrogen was determined in aliquot portions. The results appear as part of Table I.

II. The Distribution of Nitrogen in the Extracts.

(*a*) *Hydrogen peroxide extracts.* Since this was a drastic method of extraction, the extracts were studied only with respect to the distribution of the nitrogen into *ammonia* and *other* nitrogen.

(*b*) *Hydrochloric acid extracts.* These were worked on in a similar way to that in which the Haussmann distribution of an ordinary protein hydrolysate is proceeded with. The amide (or volatile base) nitrogen was estimated by distillation with magnesia after most of the free acid had

Table I. *Analyses of peaty soils and the nitrogen distribution of peat proteins as determined by the use of various extracting reagents.*

Soil code letter Col. 1	Moisture 2	Loss on ignition 3	$CaCO_3$ 4	Total nitrogen 5	% humification 6	H_2O_2 extracts: Soluble N 7	NH_3 8	N of sol. N as NH_3 9
	%	%	%	%		%	%	%
A	5·72	21·19	6·32	0·822	81·6	83·1	60·3	72·6
B	4·02	33·38	5·27	1·256	83·2	66·3	50·9	76·8
C	9·95	23·18	16·60	0·768	71·7	84·1	50·0	59·4
D	17·01	46·79	6·27	2·638	89·2	84·9	47·5	56·0
E	4·09	26·10	0·03	0·670	53·2	64·8	24·4	37·6
F	9·84	37·14	1·10	1·396	92·4	83·4	41·1	49·3
G	1·94	18·49	0·00	0·227	40·6	90·8	63·6	70·0
H	8·27	24·78	7·60	2·198	87·6	89·3	58·5	65·6
I	5·48	24·73	0·00	1·303	74·7	87·9	75·1	85·4
K	9·80	49·22	0·00	1·748	69·3	72·3	33·5	46·3
L	9·02	8·49	0·00	0·354	75·3	88·0	46·5	51·6
M	5·10	7·16	0·67	0·552	83·2	79·1	50·7	64·1

HCl extractions: Total N extd. 10	Humin N 11	Amide N 12	Mon-amino N (*M*) 13	Di-amino N (*D*) 14	*M/D* 15	KOH extractions: Total N extd. 16	Mon-amino N (*M*) 17	Di-amino N (*D*) 18	*M/D* 19	Soil code letter 20
%	% of soluble N					%	% of soluble N			
82·4	10·1	20·1	56·9	12·9	4·4	26·3	77·4	22·6	3·4	*A*
76·2	12·0	21·1	56·4	10·5	5·4	25·7	76·3	23·7	3·2	*B*
84·3	16·2	27·5	43·9	12·4	3·5	21·4	81·2	18·8	4·3	*C*
82·1	12·1	25·2	48·4	14·3	3·4	20·9	79·5	20·5	3·9	*D*
85·7	12·6	23·0	48·6	15·8	3·1	29·6	72·6	27·4	2·6	*E*
80·7	12·0	17·8	53·8	16·4	3·3	24·3	71·3	28·7	2·5	*F*
84·5	9·2	28·2	48·6	14·0	3·5	16·1	69·4	30·6	2·3	*G*
69·2	11·9	27·3	47·9	12·9	3·7	11·4	77·9	22·1	3·5	*H*
74·5	11·2	26·2	44·2	18·4	2·4	18·9	72·7	27·3	2·7	*I*
76·3	8·0	22·5	54·5	15·0	3·6	23·0	74·8	25·2	3·0	*K*
87·3	17·1	30·1	44·1	8·7	5·1	56·4	84·4	15·6	5·4	*L*
82·1	12·9	27·8	49·2	10·1	4·9	57·8	89·2	10·8	8·2	*M*

been neutralised with milk of lime. The rendering of the solution alkaline precipitated the acid-soluble humin, which from such a hydrolysate contained appreciable amounts of nitrogen. This precipitate was filtered off and well washed with hot water, the filtrate and washings being slightly acidified before being concentrated down to small volume. The diamino acids were precipitated from a volume of 150 c.c. by the addition of excess phosphotungstic-sulphuric acid solution, the phosphotungstates being redissolved in the hot liquid and allowed to crystallise out for 48 hours. The nitrogens in the humin, filtrate from the phosphotungstates, and the phosphotungstate fraction itself were determined by the Kjeldahl method, the amounts being calculated as percentages of the

dissolved nitrogens of the soils in each case. The ratio of monamino acid to diamino acid nitrogen was calculated for each soil (*v.* Table I).

(*c*) *Alkali extracts.* The extracts cited in (*c*) above contained no ammonia or other volatile base, and were proceeded with for the separation of the diamino acids from the monamino acids without further treatment. Aliquot portions were concentrated (in an open dish over a water-bath at 65–70°) and the phosphotungstates of the diamino acids precipitated in the crystalline form by the same procedure as for the acid extracts. The phosphotungstates were filtered off after standing for 48 hours, observing the same precautions in washing the precipitate. The nitrogen fractions thus separated were determined by the Kjeldahl method, the values being calculated as percentages of extracted nitrogen. The ratio of monamino acid to diamino acid nitrogen was calculated for each soil.

The distributions of nitrogen for each method of extraction are recorded in Table I.

III. Discussion of Results.

Percentage humification. The peats laid down in the presence of water uniformly showed 0·7 to 0·9 of the organic matter to be humified, whereas peat laid down under dry acid conditions contained much larger amounts of non-humified organic matter (see *E*, *K* and *G*). The boulder clay grassland soil (*L*), owing to the fibrous nature of the matter in the top three inches of soil, also showed a lower degree of humification than the normal soil *M*. The peat in *D* and *F* showed very little fibrous matter which accounted for the high degree of humification.

Hydrogen peroxide extracts. The wet peats, irrespective of soil reaction, were more easily oxidised by hydrogen peroxide and the proteins roughly yielded 70 per cent. of their nitrogen by this treatment as ammonia. The dry peats, on the other hand, yielded larger quantities of nitrogen compounds resistant to the oxidising action of the reagent, on the average, only 45 per cent. of the total nitrogen appearing as ammonia. No relation between degree of humification and amount of nitrogen appearing as ammonia finally could be inferred.

Hydrochloric acid extracts. The high percentage of nitrogen extracted by 20 per cent. hydrochloric acid was remarkable, 80 per cent., on the average, being extractable by this method. The nitrogen of calcareous peats was extracted in slightly larger amounts than that of acid peats. Fen soils were anomalous in giving the lowest percentage extraction.

The action of hot acid on the organic matter consisted amongst other

actions of (*a*) hydrolysis of the proteins, and (*b*) hydrolysis of the complex carbohydrate material. As secondary reactions may be cited the humification of part of the amino acids when heated with mineral acid in the presence of soluble carbohydrates. Consequently some of the nitrogen originally present in amino acid combination in the peat proteins appeared in the hydrolysates as part of the acid-soluble humin. (All humin terms refer to humin in the sense as applied to protein work and not to "soil humins.") Owing to the standardisation of the method of hydrolysis, it was taken for granted that the amount of humin formation was comparative for each soil and that the values for the nitrogen distributions in the humin-free extracts were sufficiently comparable for the scope of the present study. The fairly uniform values for humin nitrogen (Table I, col. 11) expressed as percentage of soluble nitrogen demonstrated this.

The amount of ammonia (and other volatile base) formed from the peat proteins by hydrolysis was from two to three times the amount commonly met with in vegetable seed proteins and in animal proteins and about four to five times that found in the protoplasmic proteins of vegetable tissue, but there was a small amount of variation in the amount of ammonia from the different soil proteins. The least amount was found in the least decomposed organic matter of the sandy forest peat. The extracted ammonia of chalky peats was a fairly uniform fraction of the extracted nitrogen.

The proteins undoubtedly existed in the soil as complex conjugated proteins, the prosthetic groups being of a carbohydrate and nucleic acid nature. The tendency of the nitrogen in the prosthetic group to be basic in nature and capable of being transformed in part to ammonia under prolonged action of hot concentrated acid would partly explain the occurrence of such a large percentage of ammonia or volatile base in the acid extract.

The ratio of monamino acid nitrogen to diamino acid nitrogen was much larger than that found for pure proteins, peat proteins being relatively low in diamino acids. The ratio was approximately 3·5 for most of the types examined, whereas the ratio for ordinary protein hydrolysates is roughly 1·5. This pointed out the fact that, in the breaking down of vegetable protein in the soil, the diamino acids suffer first. The protein of the normal soil (*M*) showed a high proportion of monamino acid nitrogen thus supporting the fact that degradation is concentrated on the diamino acids. Where the ammonia formed by this degradation cannot be further utilised or removed from the peat, amidisation of the

protein residue to some extent will take place. (The amount of free ammonia in the freshly sampled soils amounted only to 0·0016–0·0020 per cent. of the wet soils, the determinations being carried out by shaking 100 gm. of soils with a litre of *N* sodium chloride solution and determining the ammonia in the filtrate colorimetrically.) The high ammonia content of the acid extracts might further partly be explained by the diamino acids suffering mostly during the formation of humin, part of the nitrogen of the hexone bases appearing as ammonia finally. The wet basin peat (*I*) showed the highest relative content of diamino acids although the free ammonia content also was high. The dry peat on chalk (*E*) and what was originally dry acid peat (*F*) also showed relatively larger proportions of diamino acids than the calcareous peats. Calcareous peats, without exception, showed relatively low contents of diamino acids. The reaction of such alkaline peats possibly favoured the expulsion of ammonia from the soil into the atmosphere or provided a more suitable medium for slight nitrification when the soil was temporarily dry and aerated, so that, if protein degradation in the peat were dependent on the removal of ammonia either by loss into the air, solution into drainage water, removal by micro-organisms or fixation to the protein residue, the diamino acids would be broken down more in these types of peats. Thus the breaking down of the diamino acids could be regarded as a criterion of the efficiency of protein degradation in the soil. Examination of the figures for the approximately normal soils bear out this principle.

Alkaline extraction. With alkaline extraction of the peats, the proteins were partly hydrolysed and a small amount of amino acid decomposed during the process. At the same time, all volatile bases were expelled from the hydrolysate. The nitrogen compounds present in the hydrolysate, after precipitation of all humin material with calcium salt, consisted of amino acids and some non-volatile base, the latter in the separation appearing in the "filtrate." The partition of the nitrogen in the alkaline extracts gave parallel results to those obtained by acid extraction. The lowest proportion of diamino acid nitrogen was given by the organic matter of soils approaching normal, whereas the dry peats gave the highest proportion. The acid wet basin peat also had a high proportion of diamino acids. Throughout the series, the ratios of mon-amino acid nitrogen to diamino acid nitrogen for both acid and alkaline extraction were of the same order, the figures practically checking each other.

The factors which have influenced initial protein degradation in the soil were (*a*) alkalinity of medium (or better, constant non-acid reaction),

the presence of calcium bicarbonate encouraging the breaking down of the diamino acids and removing ammonia quicker than in acid soils, and (*b*) sufficient movement of water. Dry acid peats have shown less protein degradation than the wet peats. The presence of chalk in dry peats has little effect on rate of protein degradation but this may be explained in part by the comparatively low degree of humification of the organic matter of such soils. Lack of movement of water caused the accumulation of by-products of the degradation of proteins and other compounds, these being washed or allowed to diffuse away in wet peats.

SUMMARY.

The study has comprised a detailed analysis of twelve samples of soil, ten of which were samples of typical peat soils, the other two being samples of normal soils. The degree of humification of the organic matter of the samples varied, that in the wet peats being high and low in the dry peats.

Extracts of the soil were obtained by the use of boiling hydrogen peroxide, 20 per cent. hydrochloric acid and 2·5 per cent. caustic potash.

Hydrogen peroxide extracted roughly 70–80 per cent. of the soil nitrogen, 60–70 per cent. of this soluble nitrogen appearing as ammonia through the oxidising effects of the reagent. The nitrogen compounds of wet peats were more easily oxidisable to ammonia.

Hydrochloric acid extracted approximately the same amount of nitrogen as hydrogen peroxide. The nitrogen thus extracted was distributed into four fractions, ammonia, humin, monamino acid and diamino acid nitrogen. Peat proteins were found to yield by acid hydrolysis from three to five times as much amide nitrogen as pure vegetable or animal proteins, part of which might have been derived from the small amount of diamino acids broken up during hydrolysis of proteins with acids in the presence of soluble carbohydrate to form the excessive amount of acid-soluble humin present. From comparison with the values obtained for normal soils, the wider the ratio of monamino acid nitrogen to diamino acid nitrogen, the more efficient could the protein degradation in the soil be considered, whereas the effect of calcium bicarbonate and mobile water in tending to remove the products of degradation also favoured the breaking down of protein. Dry peats, on the other hand, showed a narrow ratio.

Alkali was not so destructive in its hydrolytic action as the acid, but the ratios of monamino acid to diamino acid nitrogen ran parallel to those found for the acid extracts.

Protein degradation in peaty soils as measured by the comparative breaking down of diamino acids at a faster rate than the monamino acids was favoured by wet calcareous conditions. Wet conditions alone favoured degradation slightly more than dry acid conditions. The conditions favourable for a high degree of humification also tended to favour protein degradation.

REFERENCES.

André (1902). *Compt. rend.* **135**, 1353.
Bottomley (1917). *Proc. Roy. Soc.* B, **90**, 39.
Gerlach and Densch (1913). *Bied. Zentr.* **42**, 21.
Jodidi (1910). *J. Amer. Chem. Soc.* **32**, 396.
Schreiner and Shoring (1910). *J. Biol. Chem.* **8**, 381.
Walters (1915). *J. Ind. Eng. Chem.* **7**, 860.
Valmari (1914). *Bied. Zentr.* **43**, 217.

(*Received June 5th*, 1928.)

CALORIFIC VALUE OF SOLUBLE CARBOHYDRATES IN FEEDING STUFFS.

By L. A. ALLEN, B.Sc.

(*Faculty of Agriculture, University of Reading.*)

Since the soluble carbohydrates constitute a large proportion of most feeding stuffs and are in many the preponderating factor it is desirable that as much information as possible should be known about them, particularly with regard to their energy values in relation to feeding.

The object of these investigations was to arrive at a value for the heat of combustion of those carbohydrates in feeding stuffs which are soluble in dilute acid and alkali, without isolating any of the constituents. Hitherto a combined value for the heats of combustion of the protein and carbohydrate has sufficed and for practical purposes it has often been assumed that the calorific value of the carbohydrate is the same in different feeding stuffs. There is, however, no evidence for this assumption and in fact, as a result of these experiments, it has been shown that the calorific values of soluble carbohydrates vary considerably in different feeding stuffs and, in some cases, even in different varieties of the same feeding stuff.

Experiments were first commenced on three varieties of linseed—Bombay, Plate and Baltic—and a total analysis of the dried wholemeal was made to determine the protein, fat, fibre and ash contents, carbohydrate being obtained by difference. It was found that the three specimens contained quite different percentages of the same constituents, induced probably by different soil and climatic conditions. Thus the figures for the dried wholemeals were:

Variety	Fat	Fibre	Ash	Protein	Carbohydrate
Bombay	44·22	5·01	3·14	20·46	27·17
Plate	40·17	6·57	3·28	21·12	28·86
Baltic	34·90	6·84	3·92	24·30	30·04

Samples of the dried wholemeal, fat-free meal and fibre were now prepared and the heat of combustion of each determined by means of the bomb calorimeter. From these data a combined value for the heat of combustion of the protein and carbohydrate is obtained by difference. Since the proportion of each constituent present in each of the three varieties is known it is possible in theory to obtain three simultaneous equations in two unknowns, x for the calorific value of the protein and y for that of the carbohydrate. It will be seen, however, that neither the protein nor the carbohydrate contents differ very much in the three

specimens of linseed, so that a very large possible error is introduced into the values calculated from these equations. In practice it was found impossible to attach any importance to the values so obtained. Moreover, for an investigation along these lines, it has to be assumed that the calorific values of the carbohydrate in all specimens of the same feeding stuff are identical, an assumption which further experiments tended to show is untenable.

It was decided, therefore, to adopt a different procedure, using the values for the heats of combustion of certain proteins which have already been found by other workers. Thus the proteins in certain feeding stuffs have been isolated, a complete analysis made and the calorific values determined (Benedict and Osborne, *Journal of Biol. Chem.* 1907, **3**, 119). This provides two important figures: (1) an accurate nitrogen factor for the particular protein contained in the feeding stuff under investigation; (2) the corresponding calorific value for the protein.

If, as previously, a complete analysis of a dried wholemeal is made the protein content is determined by means of the nitrogen factor given by Benedict and Osborne. For the figure for the combined heat of combustion of the protein and carbohydrate, found as before, the calorific value for the carbohydrate alone can be calculated by using the value for the heat of combustion of the protein given by Benedict and Osborne.

Calculations along these lines, when applied to the three specimens of linseed quoted above, gave figures for the calorific values of the carbohydrate which, although fairly close to each other, could scarcely be considered as identical within the limits of experimental error. Thus

Variety	Calorific value of carbohydrate
Bombay	4282 cals. per gm.
Plate	4365 ,,
Baltic	4508 ,,

Experiments were now commenced on 12 varieties of oats and a preliminary determination of the nitrogen content by the Kjeldahl method enabled four varieties—Abundance, American, Plate Winter and Grey Winter—to be selected, in two of which the protein content was considerably higher than in the other two, so that some difference might be expected in the figures for a total analysis. Such an analysis gave the following figures:

Variety	Fat	Fibre	Ash	Protein	Carbohydrate
Abundance	5·23	11·81	2·57	8·39	72·00
American	4·02	13·03	3·42	13·94	65·59
Plate Winter	5·45	13·44	3·68	14·12	63·31
Grey Winter	6·61	10·74	3·24	8·92	70·29

The protein in oats had not been investigated by the two workers mentioned above so, in this case, the nitrogen factor 6·00, as usually assumed for cereal grains, was taken in order to calculate the protein content. For the calorific value of the protein the figure 5700 was assumed as a probable average value. Since the protein value of oats is small compared with the carbohydrate content the possible error introduced by these assumptions is not very great. Support was lent to this conclusion by the fact that the calorific values of the carbohydrate in the four cases, determined as in the case of the linseed, were quite close to each other and might be considered as practically identical within the limits of experimental error. Thus:

Variety	Calorific value of carbohydrate
Abundance	4279 cals. per gm.
American	4256 ,,
Plate Winter	4320 ,,
Grey Winter	4264 ,,

Two varieties of wheat straw, "Fox" and "Red Standard," were now investigated. The same experimental procedure was adopted as before and the calorific values of the carbohydrate found to be 4863 calories in the case of the "Fox" variety and 4864 calories in the case of the "Red Standard." To arrive at these figures it was again necessary to assume the value 6 for the nitrogen factor and the figure 5700 for the calorific value of the protein. Since, however, the protein content of wheat straw is very low (*circa* 1 per cent.) the error introduced by such assumptions is negligible.

The results so far obtained seemed to indicate that the calorific value of the carbohydrate might vary considerably in different feeding stuffs. It was now thought advisable to see what results could be obtained from a study of the various feeding cakes in common use. For this purpose five specimens were chosen—palm kernel cake, ground nut cake, soya bean cake, undecorticated cotton cake, and decorticated cotton cake. In the case of soya bean and cotton cake the calorific value and the nitrogen content had been determined by Benedict and Osborne. In the case of palm kernel the figure 5·66 (an average of all the values given) was assumed for a nitrogen factor and 5650 for the calorific value of the protein. The figures for the calorific value of the carbohydrate, calculated as previously, were

Variety of feeding stuff	Calorific value of carbohydrate
Palm kernel cake	3928 cals. per gm.
Ground nut cake	3824 ,,
Soya bean cake	4334 ,,
Cotton cake (undecorticated)	4482 ,,
Cotton cake (decorticated)	4313 ,,

In calculating the figure for ground nut cake an analogy was taken from the figures given by Benedict and Osborne for vignin, the globulin in the cow pea. It was therefore assumed that 5·80 was the approximate nitrogen factor and 5700 the calorific value of the protein. It should be mentioned here that, since the protein content is high in the case of ground nut, there is possibly a larger error introduced in these assumptions and therefore less reliance can be placed on the calorific value of the carbohydrate as calculated.

In order to find values for as widely different types of feeding stuffs as possible experiments were next made with one variety of tick bean, one of wheat, one of mangold and one of cotton seed. Three varieties of cotton seed of known origin, viz. (1) Black Indian, (2) Sakellard's Soudanese, (3) Bombay, were chosen in order to see whether any difference in the calorific values of the carbohydrate, induced perhaps by climatic and soil conditions, could be detected.

Experimental.

Preparation and analysis.

The analysis in each case was conducted on the wholemeal dried in the steam oven for 24 hours. The material, wherever possible, was ground in a mill before drying. In some cases this sufficed to render the meal fine enough to obtain representative samples for analysis without much difficulty. In the case of tick bean, palm kernel cake, ground nut cake and soya bean cake a finer state of division was induced by passing through a small coffee mill after first drying. The meal was then dried again to eliminate moisture absorbed during the grinding process and kept in a glass-stoppered bottle.

In the case of oats, where the husk was too tough to be affected by a coffee mill, the wholemeal was first ground in an ordinary mill. The finely divided kernel was then separated from the husk by means of a millimetre sieve and the latter finely cut up with scissors. Husk and kernel were then well mixed together again and dried in the steam oven before analysis.

Mangold is unsuitable for drying at 100° C. since it tends to harden quickly on the outside and leave the inner portion with still a large part of its water content unevaporated. In order, therefore, to obtain a representative sample the whole mangold was first cut into two equal portions. Samples of these were extracted by boring with a circular cutter in various directions from the outer skin to the centre. The cylin-

drical portions so obtained were now dried in an air oven at 60° C. for four days, at the end of which time they had assumed a brown colour and a shrunken, crisp appearance. The mass so obtained was quickly passed through a mill, during which process it rapidly absorbed moisture and tended to "caramelise." This product was again placed in the air oven for 24 hours. Finally the material was dried, prior to combustion, in the steam oven at 100° C.

The straw could not very well be ground but, being of a more homogeneous nature than the other feeding stuffs, it was sufficient to cut it into lengths of about ¼ in. before drying in the steam oven and proceeding with the analysis.

Cotton seed could not be finely ground in a coffee mill owing to the large quantity of light fibrous material which it contained. It was found, however, that if first passed through a mill and dried in the steam oven it could conveniently be rendered much finer by passing through a mincing machine, after which it was again dried. The wheat was similarly treated.

For the analysis the following methods were adopted:

The fat or oil content was determined by extraction with pure petroleum ether in a Soxhlet apparatus. It was found that heating for two hours at 100° C. sufficed in most cases to drive off excess ether and moisture. Longer heating was avoided where possible to minimise the chance of oxidation in the case of a "drying" oil.

The protein content was determined by estimating the nitrogen by Kjeldahl's method and using a factor, a suitable one for the particular foodstuff under investigation being found in most cases by reference to the work of Benedict and Osborne (*ibid.*).

Ash was determined by heating about a gram of the dried wholemeal in a silica crucible until it had assumed a homogeneous white appearance and was constant in weight on further heating.

For determination of the fibre one to two grams of the dried wholemeal were boiled successively with 200 c.c. of 1¼ per cent. sulphuric acid and 200 c.c. of 1¼ per cent. potassium hydroxide solution for 30 minutes in each case.

The remainder of the dried wholemeal not included in these estimations was assumed to be carbohydrate and the percentage thus found by subtraction from 100 per cent.

For determinations of the heats of combustion of the wholemeal, fat-free meal and fibre the samples used were prepared in the same way as for analysis with the exception that the fibre had to be prepared on a much larger scale.

Bomb calorimetry.

The bomb calorimeter was of the Berthelot-Mahler type modified by Kroeker. A crucible of transparent silica was used in the bomb and iron wire was preferred to platinum as being easier of manipulation and more dependable.

When possible the material to be combusted was made into a pellet. In the case of a wholemeal containing a large percentage of oil this was, however, impracticable because of the loss of oil incurred during the making of the pellet. In such a case the ground material was dried and a weighed quantity transferred in the form of a loose meal to the silica crucible.

The bomb was filled with oxygen to a pressure of 20 to 25 atmospheres and connected to the terminals of a battery of eight cells providing a voltage of about 16 volts.

Twelve combustions were carried out for each feeding stuff investigated, four on the wholemeal, four on the fat-free meal, and four on the fibre, the average of the four determinations being taken in each case.

Results of Analysis.

Linseed.

Variety	Fat	Fibre	Ash	Protein	Carbohydrate
Bombay	43·69	5·08	3·14	20·46	27·63
Plate	40·05	6·27	3·28	21·12	29·28
Baltic	34·61	6·76	3·92	24·30	30·41

Heats of combustion (dry materials) in cals. per gm.

Variety	Wholemeal	Fat-free meal	Fibre
Bombay	6826	4566	4870
Plate	6591	4620	4817
Baltic	6500	4712	5051

Calorific value of protein (Benedict and Osborne) = 5635 cals. per gm.
Calorific value of carbohydrate (calculated) in cals. per gm.—

Bombay	Plate	Baltic
4282	4365	4508

Oats.

Variety	Fat	Fibre	Ash	Protein	Carbohydrate
Abundance	5·23	11·81	2·57	8·39	72·00
American	4·02	13·03	3·42	13·94	65·59
Plate Winter	5·45	13·44	3·68	14·12	63·31
Grey Winter	6·81	10·74	3·24	8·92	70·29

Heats of combustion (dry materials) in cals. per gm.

Variety	Wholemeal	Fat-free meal	Fibre
Abundance	4568	4296	4332
American	4531	4346	4379
Plate Winter	4639	4370	4397
Grey Winter	4608	4291	4591

Calorific value of protein (assumed) = 5700 cals. per gm.
Calorific value of carbohydrate (calculated) in cals. per gm.—

Abundance	American	Plate Winter	Grey Winter
4279	4258	4320	4264

Straw.

Variety	Fat	Fibre	Ash	Protein	Carbohydrate
Fox	1·04	52·75	4·52	1·18	40·51
Red Standard	0·98	53·24	2·90	1·23	41·65

Heats of combustion (dry materials) in cals. per gm.

Variety	Wholemeal	Fat-free meal	Fibre
Fox	4450	4388	4369
Red Standard	4471	4462	4361

Calorific value of protein (assumed) = 5700 cals. per gm.
Calorific value of carbohydrate (calculated) in cals. per gm.—

Fox	Red Standard
4863	4864

Palm kernel cake.

Fat	Fibre	Ash	Protein	Carbohydrate
7·67	17·94	4·42	21·85	48·12

Heats of combustion (dry materials) in cals. per gm.

Wholemeal	Fat-free meal	Fibre
4692	4346	4950

Calorific value of protein (assumed) = 5650 cals. per gm.
Calorific value of carbohydrate (calculated) = 3928 cals. per gm.

Ground nut cake.

Fat	Fibre	Ash	Protein	Carbohydrate
1·04	30·91	5·83	37·51	24·71

Heats of combustion (dry materials) in cals. per gm.

Wholemeal	Fat-free meal	Fibre
4679	4615	4805

Calorific value of protein (assumed) = 5700 cals. per gm.
Calorific value of carbohydrate (calculated) = 3824 cals. per gm.

Soya bean cake.

Fat	Fibre	Ash	Protein	Carbohydrate
3·96	5·33	6·42	46·25	38·04

Heats of combustion (dry materials) in cals. per gm.

Wholemeal	Fat-free meal	Fibre
4822	4617	4052

Calorific value of protein (Benedict and Osborne) = 5668 cals. per gm.
Calorific value of carbohydrate (calculated) = 4310 cals. per gm.

Cotton cake (decorticated).

Fat	Fibre	Ash	Protein	Carbohydrate
9·84	14·30	6·66	36·33	32·87

Heats of combustion (dry materials) in cals. per gm.

Wholemeal	Fat-free meal	Fibre
4962	4528	4397

Calorific value of protein (Benedict and Osborne) = 5596 cals. per gm.
Calorific value of carbohydrate (calculated) = 4313 cals. per gm.

Cotton cake (undecorticated).

Fat	Fibre	Ash	Protein	Carbohydrate
4·78	25·01	5·89	24·38	39·94

Heats of combustion (dry materials) in cals. per gm.

Wholemeal	Fat-free meal	Fibre
4678	4475	4427

Calorific value of protein (Benedict and Osborne) = 5596 cals. per gm.
Calorific value of carbohydrate (calculated) = 4482 cals. per gm.

Tick bean.

Fat	Fibre	Ash	Protein	Carbohydrate
1·61	8·27	3·30	25·59	61·23

Heats of combustion (dry materials) in cals. per gm.

Wholemeal	Fat-free meal	Fibre
4441	4373	4217

Calorific value of protein (Benedict and Osborne) = 5620 cals. per gm.
Calorific value of carbohydrate (calculated) = 4109 cals. per gm.

Fox wheat.

Fat	Fibre	Ash	Protein	Carbohydrate
1·52	2·05	1·85	11·04	83·54

Heats of combustion (dry materials) in cals. per gm.

Wholemeal	Fat-free meal	Fibre
4292	4229	5518

Calorific value of protein (Benedict and Osborne) = 5720 cals. per gm. (This is the mean of the values for glutenin and gliadin.)
Calorific value of carbohydrate (calculated) = 4095 cals. per gm.

Mangold.

Fat	Fibre	Ash	Protein	Carbohydrate
0·13	6·98	5·78	6·88	80·23

Heats of combustion (dry materials) in cals. per gm.

Fat-free meal	Fibre
3796	4396

Since the fat content was so small the calorific value of the fat-free meal might be considered the same as that of the wholemeal within the limits of experimental error. The heat of combustion of the wholemeal was therefore not determined directly.

Calorific value of protein (assumed) = 5620 cals. per gm.
Calorific value of carbohydrate (calculated) = 3860 cals. per gm.

Cotton seed.

Variety	Fat	Fibre	Ash	Protein	Carbohydrate
Black Indian	21·76	21·74	4·82	18·42	33·26
Soudanese	23·31	24·49	4·66	23·22	24·32
Bombay	17·85	26·42	4·93	17·81	32·99

Heats of combustion (dry materials) in cals. per gm.

Variety	Wholemeal	Fat-free meal	Fibre
Black Indian	5559	4476	4492
Soudanese	5615	4523	4554
Bombay	5268	4432	4466

Calorific value of protein (Benedict and Osborne) = 5596 cals. per gm.
Calorific value of carbohydrate (calculated) in cals. per gm.—

Black Indian	Soudanese	Bombay
4493	4334	4438

Table I. *Summary of results.*

Calorific value of soluble carbohydrates

Feeding stuff	Variety	Calorific value	Percentage
Linseed	Bombay	4282	98·80
	Plate	4365	100·71
	Baltic	4508	104·01
Oats	Abundance	4279	98·73
	American	4258	98·25
	Plate Winter	4320	99·68
	Grey Winter	4264	98·39
Straw	Fox	4863	112·20
	Red Standard	4864	112·22
Palm kernel cake	—	3928	90·63
Ground nut cake	—	3824	88·24
Soya bean cake	—	4310	99·45
Cotton cake	Decorticated	4313	99·52
	Undecorticated	4482	103·42
Tick bean	—	4109	94·81
Fox wheat	—	4095	94·49
Mangold	—	3860	89·06
Cotton seed	Black Indian	4493	103·67
	Soudanese	4334	100·00
	Bombay	4438	102·40

Table II.

	Analysis			Calorific value		
Feeding stuff	Fibre	Protein	Carbo-hydrate	Fibre	Protein	Carbo-hydrate
Linseed (Bombay)	5·08	20·46	27·63	4870	5635	4282
(Plate)	6·27	21·12	29·28	4817	5635	4365
(Baltic)	6·76	24·30	30·41	5051	5635	4508
Oats (Abundance)	11·81	8·39	72·00	4332	5700	4279
(American)	13·03	13·94	65·59	4379	5700	4258
(Plate Winter)	13·44	14·12	63·31	4397	5700	4320
(Grey Winter)	10·74	8·92	70·29	4591	5700	4264
Straw (Fox)	52·75	1·18	40·51	4369	5700	4863
(Red Standard)	53·24	1·23	41·65	4361	5700	4864
Palm kernel cake	17·94	21·85	48·12	4950	5650	3928
Ground nut cake	30·91	37·51	24·71	4805	5700	3824
Soya bean cake	5·33	46·25	38·04	4052	5668	4310
Cotton cake (Decorticated)	14·30	36·33	32·87	4397	5596	4313
(Undecorticated)	25·01	24·38	39·94	4427	5596	4482
Tick bean	8·27	25·59	61·23	4217	5620	4109
Fox wheat	2·05	11·04	83·54	5518	5720	4095
Mangold	6·98	6·88	80·23	4396	5620	3860
Cotton seed (Black Indian)	21·74	18·42	33·26	4492	5596	4493
(Soudanese)	24·49	23·22	24·32	4554	5596	4334
(Bombay)	26·42	17·81	32·99	4466	5596	4438

Discussion of Results.

The results are summarised in Tables I and II and they indicate that the calorific values of the carbohydrates in different feeding stuffs are very variable quantities. This is best brought out in the last column of Table I where results are expressed as percentages. The standard of reference taken is that for Soudanese cotton seed. The reasons for this are briefly: (1) the globulin of the cotton seed which was isolated by Benedict and Osborne represents very nearly the whole of the protein matter of that seed and therefore the error introduced by calculating the heat of combustion of the protein on the assumption that it is *all* of one kind is negligible; (2) the average of the twenty values obtained for the carbohydrates of the different feeding stuffs is 4310 calories which is very near the value for Soudanese cotton seed (4334).

The values shown in the third column of Table I are striking in that, generally speaking, they represent a considerably higher value than is usually assigned to the simpler carbohydrates of known constitution of which the heats of combustion have been directly determined. Thus Atwater (*U.S. Dept. of Agric., Office of Expt. Stations, Bulletin No.* 21, 1895) quotes the following values as determined by Stohmann and Langbein:

Pentoses		Hexoses	
Arabinose	3722 cals.	Sorbinose	3715 cals.
Xylose	3746 ,,	Galactose	3722 ,,
Fucose	4341 ,,	Dextrose	3743 ,,
Rhamnose	4379 ,,	Fructose	3755 ,,

Disaccharides		Trisaccharides	
Cane sugar	3955 cals.	Melitriose	4021 cals.
Milk sugar	3952 ,,	Melizitose	3914 ,,
Maltose	3949 ,,		
Trehalose	3947 ,,		

Polysaccharides	
Glycogen	4192 cals.
Cellulose	4185 ,,
Starch	4183 ,,
Dextrin	4112 ,,
Inulin	4134 ,,

The heats of combustion of these carbohydrates increase, broadly speaking, with increasing molecular complexity. Thus the heats of combustion of monosaccharides, disaccharides and polysaccharides increase in that order by about 200 calories per gram. When we come to the crude fibre as estimated by the standard method we see that the calorific values (Table II) are considerably higher than those assigned to polysaccharides of simpler constitution. The investigations of Schulze, König,

Tollens and others have shown that this crude fibre is a mixture of variable composition containing cellulose, pentosans and lignins, some of which are dissolved by acid and alkali, some are partially soluble and some resist the action altogether.

In estimating the carbohydrate content and its calorific value by the method adopted in this paper these substances must enter into consideration. In fact it would appear that these bodies, intermediate between the polysaccharides and the insoluble woody fibrous substances, may be responsible for giving a high value to the heats of combustion of the carbohydrate as calculated.

It will be seen that the values vary from 3824 calories in the case of ground nut cake to 4864 calories in the case of straw, or, expressed as percentages, from 88·24 per cent. to 112·22 per cent. This represents a very considerable variation and it seems that the same factors may be responsible for this as were adduced to explain the generally high values obtained for the carbohydrates—*i.e.* the presence of carbohydrates of a complex nature which are either wholly or partially hydrolysed by dilute acid and alkali and must therefore enter into consideration in the calculations.

In conclusion the author wishes to express his thanks to Prof. H. A. D. Neville for his valuable help and constant interest in this work, and to the University authorities for a grant in aid of research.

(*Received June 13th*, 1928.)

A SHORT NOTE ON THE NUTRITIVE VALUE OF LINSEED CAKE.

By JAMES STEWART, M.A., B.Sc.
(Institute of Animal Pathology, Cambridge University.)

Prof. T. B. Wood in the November issue of the *Journal of the Ministry of Agriculture* discussing the known methods of estimating the nutritive values of foodstuffs says, "there is a method which is within the scope of any experimenter and is capable of yielding accurate results of great practical value," and he goes on to give examples, in the estimating of the nutritive value of swedes, kale, etc., using the results of an experiment which entailed the use of 40 to 120 animals. From these experiments he gets results showing a very satisfactory agreement between experiment and calculation, notwithstanding that there must be a slight experimental error in the calculation of food consumed.

At this Institute, there is at present being conducted an enquiry into the injurious effects of feeding an excess of protein food to lambs, and in the course of this experiment one lamb has been on a ration, of nothing but linseed cake, from July 7 to December 7, 1927 (22 weeks). During all that time the lamb was kept in a metabolic cage whereby its consumption was rigorously controlled and its change of weight regularly determined, so here the writer thought was a very suitable opportunity of finding how near the results of a single animal would conform to Prof. Wood's figures and curves, as the animal being quiet and quite contented could not waste an undue amount of starch equivalent in movement.

Table I gives the consumption of linseed cake during the experimental period and Table II the change in weight.

Table I.

Date	Amount of linseed cake consumed
July 7–Aug. 1	33,799 gm.
Aug. 2–Sept. 2	41,495
Sept. 3–Oct. 2	42,470
Oct. 3–Oct. 30	38,051
Oct. 31–Dec. 7	47,134

Therefore average weekly consumption = 20·3 lb. of linseed cake of 88 per cent. dry matter.

Table II.

Date	Weight of lamb
July 7	124 lb.
Aug. 2	126
Sept. 3	$127\frac{1}{2}$
Oct. 3	139
Oct. 31	149
Dec. 7	159

Therefore average weight during experimental period = $141\frac{1}{2}$ lb.

Calculation of starch equivalent of linseed cake from the equation

$$R = M + GK.$$

Average live weight of animal during experimental period = $141\frac{1}{2}$ lb.

Therefore $\qquad M = 11{\cdot}07$ lb. S.E. per week[1].

Average ration per week during experimental period, linseed cake 20·3 lb. = $\cdot 203x$ lb. S.E. if x = S.E. in 100 lb.

Therefore $\qquad R = \cdot 203x$ lb. S.E. per week.

Experimental period covered 5 months. Middle point = $2\frac{1}{2}$ months at which $K = 2{\cdot}33$ lb. S.E. per lb. gain[2].

Average gain in live weight per week:

$$G = 1{\cdot}59 \text{ lb.}$$

Therefore if $R = M + GK$

$$\cdot 203x = 11{\cdot}07 + 2{\cdot}33 \times 1{\cdot}59$$

$$= 14{\cdot}7747.$$

Therefore $\qquad x = 72{\cdot}78$ lb. S.E. per 100 lb. linseed cake.

Kellner's figure for starch equivalent per 100 lb. of linseed cake = 73 for cake of 88 per cent. dry matter. R. G. Linton, in his *Animal Nutrition*, gives a figure = 72. Thus we get from a single lamb living under conditions very suitable for getting accurate data a figure, as calculated from Prof. Wood's curves, which agrees most satisfactorily with that of Kellner's.

[1] See Fig. 1, p. 698, *J. Min. Agric.* Nov. 1927.
[2] See Fig 2, p. 699, *J. Min. Agric.* Nov. 1927.

(*Received June* 15*th*, 1928.)

CERTAIN ACID SOILS AND GROWTH OF SUGAR BEET.

By the late GEORGE NEWLANDS, M.A., B.Sc.
(Soils Research Department, North of Scotland College of Agriculture, Aberdeen.)

Introduction.

In the course of advisory work in north-east Scotland instances of failure of sugar beet crops were met with and examination of the soils concerned, along with others carrying more or less successful crops, provided an opportunity of investigating the inter-relationship of certain physico-chemical properties of the soil and the relation of these to crop yield. In view of the well-known adverse effects of acid conditions on the growth of sugar beet, the soils were, naturally, examined for acidity and lime requirement. They were also examined for readily extractable calcium and humus content and in particular instances for total absorption capacity for bases, titratable acidity and degree of saturation. Field and textural conditions had also to be considered and examination was made in these respects. The general results for all the soils will be dealt with first, and the more detailed examination of one of the soils taken later.

The Soils Examined.

Except where mentioned later the soils were of glacial drift origin, the drift having been derived from granitic and metamorphic rocks (schists and gneiss). Examination in the field showed that, while conditions varied somewhat, in no instance were they unfavourable for beet growing, in so far as soil depth, drainage and freedom from pan near the surface were concerned. None of the soils appeared too heavy in texture and the results of mechanical analyses bear this out.

Mechanical Analysis and Crop Growth.

Analysis was performed on the fine earth passing a 1 mm. sieve, by the method recommended by the Agricultural Education Association (1). The results are collected in Table I, notes on crop growth also being included. With regard to crop growth, the term "good" is to be understood in a relative sense, the best yield being only 11 tons unwashed beets per acre.

Table I. *Mechanical analyses—results as percentages of air-dried fine earth passing a 1 mm. sieve*

Soil sample ...	E.	N. 1	N. 2	N. 3	N. 4	M.H.	M.
Coarse sand ...	23·08	20·46	20·51	20·97	20·73	32·37	35·81
Fine sand ...	22·33	24·99	24·88	25·67	26·09	22·71	24·36
Silt	12·10	15·37	15·12	15·87	14·75	9·72	8·20
Fine silt ...	15·00	14·25	13·35	13·87	13·87	11·47	10·00
Clay	13·90	12·25	11·90	12·12	11·12	8·27	8·90
Loss by solution	1·94	1·81	1·81	1·75	1·90	2·18	1·54
Loss on ignition	9·20	8·73	9·72	7·93	9·36	9·23	8·69
Moisture ...	3·20	3·00	3·80	2·70	2·90	3·70	2·80
Total	100·75	100·86	101·09	100·88	100·72	99·65	100·30
Crop growth ...	Good	Very poor	Very poor	Fairly good	Good	Good	Good

Soil sample ...	B.	G. 1	G. 3	W.	Ga.	Gb.	H.
Coarse sand ...	35·49	33·22	36·92	45·52	47·50	57·64	38·38
Fine sand ...	25·03	25·67	21·58	21·73	20·62	15·02	25·36
Silt	9·94	10·66	12·05	10·10	6·25	5·41	9·49
Fine silt ...	11·31	9·25	9·50	8·20	8·12	5·75	11·36
Clay	6·86	5·90	5·70	5·60	4·94	4·65	3·14
Loss by solution	1·65	1·96	1·74	1·51	1·45	1·38	1·96
Loss on ignition	6·50	9·58	9·88	6·20	9·73	8·65	7·23
Moisture ...	2·85	4·30	2·80	2·00	2·27	2·00	2·88
Total	99·63	100·54	100·17	100·86	100·88	100·50	99·80
Crop growth ...	Failure	Fairly good	Failure in places	Good	Failure	Good	Poor, irregular

Within the range of texture represented, correlation between textural grade and crop yield is not observed. Soils E. and W., for example, carried approximately the same crop, the former being one of the heaviest drift soils examined while the latter was one of the lightest and of fluvio-glacial origin. The favourable characteristics which they had in common were good depth of soil and freedom of subsoil. Again in the case of samples N. 1, 2, 3 and 4, all drawn from the same field, and all very similar in mechanical composition, it is obvious that it is not the textural factor which is the cause of the difference in crop growth.

EXPERIMENTAL METHODS.

*p*H *value.* The determination of *p*H value was made by means of the quinhydrone electrode using a saturated calomel electrode and a saturated potassium chloride and agar bridge. 10 gm. of air-dried fine earth with 20 c.c. of distilled water (ammonia and CO_2 free) were used for a determination. As it was found that variations in readings might occur according to whether the platinum foil and the tip of the agar bridge dipped into the paste of soil and liquid or into supernatant liquid, in practice the platinum electrode and the tip of the bridge were immersed in the soil paste.

Lime requirement. This was determined by the Hutchinson and MacLennan (2) method, using 10 gm. air-dried fine earth with 200 c.c. of $N/50$ calcium bicarbonate solution and shaking for 3½ to 4 hours.

Readily extractable calcium. This was determined by the use of a $N/20$ HCl solution following the method of Gedroiz (3). For the present purpose it was considered sufficient to cease extraction when 250 c.c. of filtrate had been collected and to determine the calcium content of this. Gedroiz recommends leaching until the filtrate shows no calcium present on being tested with ammonium oxalate. This does not necessarily give exchangeable calcium in the sense used by Hissink and the term is therefore not used in the present connection.

Table II.

Soil	% readily extractable calcium	pH value	% lime requirement as $CaCO_3$	% humus soluble in H_2O_2	Remarks on crop
B.	·064	4·95	·24	3·26	Failure
N. 1	·080	4·85	·39	5·08	Very poor growth
N. 2	·084	4·90	·40	6·00	Very poor growth
Ga.	·108	5·15	·36	5·28	Failure
H.	·116	5·20	·22	3·82	Poor, irregular
N. 3	·121	5·30	·27	4·00	Fairly good
W.	·148	5·20	·23	3·86	Good, 11 tons per acre unwashed beet
G. 3	·150	5·25	·42	7·33	Failure in places
N. 4	·161	5·40	·26	5·68	Good, better than at N. 3
M.H.	·186	5·70	·21	4·78	Good, 10 tons per acre unwashed beet
G. 1	·188	5·40	·34	6·62	Fairly good
E.	·196	5·45	·29	5·36	Good, 10½ tons per acre unwashed beet
M.	·204	5·95	·25	2·60	Good, 10½ tons per acre unwashed beet
Gb.	·256	6·10	·16	5·74	Good

Humified organic matter. It is recognised that the "loss on ignition" gives only a rough approximation to the organic content of the soil and in view of the part played by the humus in absorption and exchange phenomena, it was considered that a figure of greater value might be obtained by determining the soluble humus by treatment with hydrogen peroxide according to the method of Robinson and Jones (4). 5 gm. of air-dried fine earth were heated with 50 c.c. of peroxide in a steam bath, followed by further additions of the peroxide until all effervescence ceased. The treated soil was then transferred to a filter paper in a funnel and thoroughly washed with warm water. As the filtrate contained a slight suspension of clay and probably some mineral matter in solution, it was evaporated down to small bulk, transferred to a weighed basin, taken to dryness and ignited[1]. The washed soil was transferred from the

[1] Groves (5) also takes the precaution to allow for mineral matter in filtrate.

filter to a beaker, and the filter paper freed as far as possible from adhering fine material by means of a jet from a wash-bottle. The washed paper was placed in the basin, dried and ignited. Any loss of combined water from the small amount of clay left adhering to the paper is negligible. The soil residue was transferred from the beaker to the basin and dried in a steam oven to constant weight at 98° C. The loss in weight due to peroxide treatment, minus the moisture content in the air-dried soil, gave the soluble humus. The results were calculated to the percentage of the air-dried fine earth and are included in Table II along with those for *p*H value, lime requirement and readily extractable calcium, the soils being arranged in order of increasing content of the extractable calcium.

DISCUSSION OF GENERAL RESULTS.

It will be seen from Table II that there is a general relation between the percentage of readily extractable calcium and the *p*H value, and that these are correlated with crop growth. At the top of the table are to be found the soils with poorest growth corresponding to low calcium content and low *p*H value, while at the other end are the soils with good yields and higher *p*H value and calcium content. Generally, when the percentage of extractable calcium is below 0·12 and the *p*H value below 5·3, growth of beet is poor, an exception with regard to *p*H being found in soil W. which showed one of the best yields at 5·2 *p*H. As already mentioned this soil was of fluvio-glacial origin and was a deep soil with free subsoil, very favourable in physical conditions for the development of large tap roots. Each of the soils examined is, in the light of experience on the Continent, too acid for good growth of beet, for the highest *p*H recorded is only 6·1, whereas any value below 6·5 is regarded as unfavourable to full growth. The lime requirement figures do not correlate well with those for extractable calcium and acidity over the whole range of the soils. It is only when samples of the same soil type are compared that correlation with these values and with growth of the beet is observable. Samples N. 1, 2, 3 and 4 furnish a good instance of this. As mentioned previously these are from the same field and belong to one type. N. 1 and N. 2, from areas where beet growth was very poor, agree closely in *p*H value, lime requirement and readily extractable calcium and are distinct in these values from N. 3 and N. 4 where growth was much better. N. 3 and N. 4 agree in *p*H value and lime requirement, but the extractable calcium content is somewhat higher in N. 4 and corresponds with better growth of beet there than at N. 3.

The results for Ga. and Gb. offered a similar instance of the correlation between the three values being discussed and their relation to the growth of beet, when samples from "good" and "bad" areas in the same field, and from the same soil type, are compared, the soil in this case being derived from a sandy river alluvium. Crop failure at Ga. is associated with a lower extractable calcium content, lower pH value and higher lime requirement than at Gb., where crop growth was good. Again G. 1 and G. 3 from another field on the same farm, but from a soil of the usual glacial drift of the district, may be similarly compared. It may be mentioned that lime had been applied to both fields of this farm, and the results, taken in conjunction with examination in the field, point to unequal distribution of the lime.

With regard to the organic content of the soil, the important part played by the humified portion in base exchange and related phenomena is generally recognised. Insufficient data have been collected to determine with accuracy the relative absorptive power of colloidal humus to that of colloidal clay, but Hissink (6) found from studies of well-saturated Dutch soils that, weight for weight, the humus absorbed about five times the amount of calcium that the clay did, while the results of Page and Williams (7) for a Rothamsted soil indicate that the absorptive power of the organic matter (determined by loss on ignition) is about twice that of the clay and very fine silt. The present results do not provide material for a general discussion, but several instances are afforded which show the connection between the content of humus and the lime requirement, especially when soils of about equal extractable calcium content are compared, such as W. and G. 3, or M.H. and G. 1. The lime requirement is correlated in these with the soluble humus, and not with the clay or clay plus fine silt, as reference to Tables I and II will show.

Further Examination of Samples N. 1–4.

The samples N. 1–4 were further investigated as to exchangeable calcium, absorption capacity for bases, titratable acidity and degree of saturation.

Experimental Methods.

Exchangeable calcium was determined by extraction with $N/20$ HCl, 25 gm. of soil being used and leaching carried on until a litre of filtrate had been collected, the first and second half-litres being collected separately. The results are given in Table III, the figures for both first and second half-litres of filtrate being given, as well as the results

obtained according to whether the second is added to or subtracted from the first.

Table III. *Percentage of calcium extracted by N/20* HCl.

Soil sample ...		N. 1	N. 2	N. 3	N. 4
500 c.c. filtrate.	1st	·070	·086	·115	·158
	2nd	·007	·006	·007	·007
	Sum	·077	·092	·122	·165
	Difference	·063	·080	·108	·151

A consideration of these results raises the question of which figure is to be adopted to express exchangeable calcium. It will be seen that the amount found in the second half-litre may be 10 per cent. of that in the corresponding first half-litre, and it is apparent that in dealing with soils having low amounts of extractable calcium that the particular procedure adopted in arriving at the exchangeable calcium becomes important. It is doubtful whether the calcium present in the second portion of the filtrate can be regarded as due to "solubility effects" as distinct from calcium in "exchangeable" form.

Titratable acidity and absorption capacity. To determine these a method based on that of Gedroiz (8) combined with that of Bobko and Askinasi (9) was employed. A weighed amount of fine earth (10 or 25 gm.) was treated with 50 c.c. of $N/1$ $BaCl_2$ solution. Soil and solution were thoroughly stirred and allowed to remain in contact for some time. The soil was then washed with the $BaCl_2$ solution on to a filter paper in a funnel and leached with solution until 2½ litres of filtrate were obtained, the filtrate being collected in half-litre lots. Each lot was titrated with approximately $N/10$ NaOH solution (free from carbonate) in the presence of "universal" indicator, until the same colour was developed as was given by the original barium solution which was nearly neutral to the indicator.

In the first experiment 25 gm. of soil were used, but as titratable amounts of acid were still present in the last 500 c.c. of filtrate from the more acid soil samples, operations were repeated using 10 gm. of soil. In the case of the 10 gm. portions, only very small amounts of acidity were found in the final half-litres and the process of displacement of hydrogen by barium ions with the concentration of solution used was regarded as completed. The results are given in Table IV.

Absorption capacity. The soil after being saturated with barium as described was next washed with distilled water (CO_2 free) until barium was no longer detected in the filtrate. The absorbed barium was then displaced by leaching with $N/20$ HCl, a litre of filtrate being collected in half-litre lots where 25 gm. of soil had been used, and until no further

barium was detected in the filtrate in the case of the 10 gm. portions. The barium in the filtrate was detected as $BaSO_4$.

Table IV. *Titratable acidity on treatment with N/1* $BaCl_2$ *solution.*

Results stated as c.c. NaOH.

Soil samples ...	N. 1		N. 2		N. 3		N. 4	
500 c.c. filtrate	25 gm. soil	10 gm. soil	25 gm. soil	10 gm. soil	25 gm. soil	10 gm. soil	25 gm. soil	10 gm. soil
1st	8·20	4·75	7·50	4·65	3·90	2·50	2·60	1·85
2nd	2·20	0·75	2·00	0·75	1·20	0·45	0·45	0·40
3rd	1·15	0·55	1·20	0·55	0·60	0·30	0·30	0·25
4th	0·75	0·25	0·80	0·30	0·40	0·20	0·20	0·20
5th	0·60	0·10	0·60	0·10	0·40	0·05	0·05	0·05
Total	12·90	6·40	12·10	6·35	6·50	3·50	3·60	2·75
c.c. *N*/10 NaOH per 100 gm.	45·50	58·90	44·50	58·40	23·90	32·20	18·70	25·30

Degree of saturation. This was deduced from the total absorption capacity and the titratable acidity values. The latter were expressed in terms of barium and the amounts so found deducted from those for total absorption. The difference gives the amounts of barium equivalent to the original bases replaced. This difference expressed as a percentage of the total absorption gives the degree of saturation. The results are given in Table V.

Table V.

Soil sample ...	N. 1	N. 2	N. 3	N. 4
Crop growth ...	Very poor	Very poor	Fairly good	Good
% humus sol. in H_2O_2 ...	5·08	6·00	4·00	5·68
% lime requirement as $CaCO_3$ ...	0·39	0·40	0·27	0·26
*p*H value ...	4·85	4·90	5·30	5·40
% readily extractable Ca ...	0·08	0·084	0·121	0·161
Titratable acidity as c.c. *N*/10 acid/100 gm. soil	58·90	58·40	32·20	25·30
Total absorption capacity as % Ba absorbed	0·674	0·700	0·636	0·807
Absorption capacity (after HCl treatment) ...	0·649	0·549	0·489	0·745
Degree of saturation ...	40·0 %	42·7 %	65·2 %	78·4 %

Discussion of Results for Samples N. 1–4.

The results for titratable acidity and degree of saturation show clearly the agreement between N. 1 and N. 2 already brought out by *p*H value, lime requirement and extractable calcium, and also the difference between N. 1 and N. 2 on the one hand and N. 3 and N. 4 on the other. Further, the difference which exists between N. 3 and N. 4 is now brought out more clearly than by the *p*H value and lime requirement methods. The less acid condition of N. 4 when compared with N. 3 is in accordance with the greater content of readily extractable calcium in the former.

According to the total absorption capacity for bases the samples fall

into the following order, going from least capacity to greatest, N. 3, N. 1, N. 2, N. 4. The differences are not accounted for by differences in clay content nor in clay plus fine silt content. There is a certain amount of correlation with the humus content which is lowest in N. 3, with N. 1 next in order, but in N. 2 and N. 4 it is very nearly equal and the greater absorption in N. 4 is not accounted for.

The high absorption in N. 4 is associated with high titratable acidity. This means that there are relatively fewer H ions to displace by the barium. The difficulty of displacing H ions is recognised, and saturation with barium may not have been achieved, by the methods adopted, in any of the four samples, but would be most nearly complete in N. 4. In other words the higher percentage of replaceable bases in this sample might account for the higher absorption of barium. But these considerations do not appear to afford a satisfactory explanation, for when the absorption capacity of the samples was estimated in the same way with $BaCl_2$ solution after replacement of the bases originally present by hydrogen, through treatment with $N/20$ HCl, N. 4 still showed greatest absorption, although the absorption capacity in all four samples was lower when compared with that of the original soil.

SUMMARY AND CONCLUSIONS.

1. Variations in growth of sugar beet on certain soils from north-east Scotland were investigated by examination of the soils with regard to field conditions, mechanical composition, *p*H value, lime requirement, readily extractable calcium and humified organic matter.

2. Field conditions and mechanical composition did not account for the variations in growth of the beet.

3. A certain degree of correlation was found between *p*H value, readily extractable calcium and growth of beet. In general when the *p*H was below 5·3 and extractable calcium below 0·12 per cent., growth was poor or failed. Above these figures it was good, but only relatively so, since all the soils were below 6·2 in *p*H value.

Over the whole range of soils lime requirement did not correlate well with the other values, but when samples from one soil type were compared, correlation was observed between all three and with beet growth.

4. When soils of equal extractable calcium content were compared, that with higher humus content had the higher lime requirement.

5. Four samples from one soil type, two from areas of poor beet growth and two from areas of better growth, were further examined as

to exchangeable calcium, absorption capacity for base, titratable acidity and degree of saturation.

6. For these four areas the results for pH value, lime requirement, exchangeable calcium, titratable acidity and degree of saturation all correlate well with each other and with growth of beet.

REFERENCES.

(1) Agric. Educ. Assoc. Sub-Committee (1926). *J. Agric. Sci.* **16**, 123.

(2) Hutchinson, H. B. and MacLennan, K. (1915). *J. Agric. Sci.* **7**, 73.

(3) Gedroiz, K. K. (1923). *Soil Sci.* **16**, 473–4.

(4) Robinson, G. W. and Jones, J. O. (1925). *J. Agric. Sci.* **15**, 26.

(5) Groves, R. C. (1928). *J. Agric. Sci.* **18**, 203.

(6) Hissink, D. J. (1926). *Trans. 2nd Commission, Intern. Soc. of Soil Sci.* vol. A, p. 183.

(7) Page, H. J. and Williams, W. (1925). *Trans. Faraday Soc.* **20**, 580.

(8) Gedroiz, K. K. (1927). *Trans. 2nd Commission, Intern. Soc. of Soil Sci.* vol. B, p. 191.

(9) Bobko, B. W. and Askinasi, D. L. (1927). *Trans. 2nd Commission, Intern. Soc. of Soil Sci.* vol. B, p. 188.

(*Received June 28th*, 1928.)

THE MECHANISM OF CELLULOSE DIGESTION IN THE RUMINANT ORGANISM.

II. THE TRANSFORMATION OF CELLULOSE INTO GLUCOSE BY THE AGENCY OF CELLULOSE-SPLITTING BACTERIA.

By H. E. WOODMAN, M.A., Ph.D., D.Sc.
and J. STEWART, M.A., B.Sc.
(The Institutes of Animal Nutrition and Animal Pathology, Cambridge University.)

Introduction.

An attempt was made in a recent communication (1) to propound a theory in connection with the digestion of cellulose in the ruminant organism which should be compatible with Kellner's findings as to the value of digestible fibre in the fattening of ruminants. It was shown that the generally accepted theory, that cellulose is digested by bacterial agency in the rumen with the production of organic acids and gaseous products, such as methane, hydrogen and carbon dioxide, failed entirely to account for the equal values of digestible fibre and starch for fat production in the ruminant animal. This could only be explained by assuming that glucose (or some other sugar capable of hydrolysis to glucose) was formed as a primary product of the action of bacteria on cellulose, and that, as with digestible carbohydrates originally present in the food, only about 8 per cent. of the sugar so formed underwent further bacterial breakdown into organic acids and gases, the remainder being available for absorption into the organism in the form of glucose. On this assumption, it would follow that every gram of fibre so digested would yield to the organism as much glucose as would a gram of starch, and in this way Kellner's practical finding would be capable of explanation.

It was clear, however, that the tenability of such a hypothesis depended upon the production of evidence to support the view that glucose arises as an intermediate product when cultures of cellulose-fermenting bacteria are brought into contact with cellulose in artificial media. The only available evidence was that forthcoming from the results of investigations carried out by Pringsheim (2), who, by the controlled action of cellulose-splitting micro-organisms on filter paper, was able to prove the presence of both glucose and cellobiose in the reaction mixture. This result suggests a parallelism between the mode of digestion of starch

by enzymes and that of digestion of cellulose by bacteria, such as is shown by the following scheme:

Enzyme digestion:

Starch → maltose (glucose-α-glucoside) → glucose.

Bacterial digestion:

Cellulose → cellobiose (glucose-β-glucoside) → glucose.

It was felt, however, that it would be unsafe to base the new theory of cellulose digestion on the findings of a single investigation. Moreover, some doubt appears to have been cast on the results of this old German investigation by authorities in this country, and although many workers have, in recent years, prosecuted researches into the gas-producing powers of cellulose-fermenting organisms, no one has attacked the problem from the standpoint of glucose production from cellulose by such agency. It appeared desirable, therefore, that further work should be carried out along the lines of Pringsheim's original experiments. This, accordingly, has been done, and it may be stated quite briefly at this point that no difficulty has been experienced in confirming Pringsheim's results.

Isolation and Description of Cellulose-splitting Micro-organism.

The following medium[1] was used for starting the culture:

Calcium carbonate	1·20 gm.
Sodium phosphate	0·50 ,,
Ammonium sulphate	0·25 ,,
Potassium chloride	0·10 ,,
Tap water	100 c.c.

As a source of cellulose, filter paper, torn by hand into small pieces and then well pulped in boiling water, was used, 2 gm. being added for each 100 c.c. of medium. The salts were weighed out separately into a small flask and the filter paper and 100 c.c. of tap water added, the flask and its contents being then sterilised in an autoclave. The contents were then sown with about 5 gm. of well-rotted dung from an old heap consisting mainly of horse dung. The flask was then placed in an incubator at 65° C. The fermentation which then took place was almost identical with that described by Viljoen, Fred and Peterson (3). After

[1] This medium was used at the suggestion of Dr Harold Raistrick, to whom the writers are also indebted for much useful information and advice in the initial stages of this investigation.

about 24 hours' incubation, gas bubbles began to rise to the surface of the liquid. After 36 hours gas formation became so considerable that the bulk of the filter paper was carried to the surface of the liquid, forming a "head." At this stage the pulp had turned yellowish brown in colour, and when the fermentation was complete, which was usually the case after 5 to 7 days, the "head" dropped, and the residue consisted of a yellowish brown sediment, calcium carbonate, bacterial residues and some unchanged filter paper. Transfers of 5 c.c. portions were then made to fresh flasks of cellulose and medium, and by this method of sub-culturing every seventh day, a pure culture of micro-organisms was soon obtained. Growing the organism at 37° C. was attempted unsuccessfully, and all the subsequent incubations were therefore carried out at 65° C.

The peculiar fact was noted that if, in preparing the cellulose for the media, the filter paper were cut with scissors, instead of being torn by hand, then the subsequent fermentation was delayed by about 48 hours. This was doubtless due to the circumstance that the frayed edge of the hand-torn filter paper was more readily attacked by the bacteria than the straight edge of the scissors-cut paper.

No difficulty has been experienced in preserving the activity of the cellulose-splitting micro-organisms by the method of sub-culturing described above. At the time of writing, the fifty-second transfer is being made, and the cultures have shown no diminution whatsoever in their power of fermenting the pulped filter paper.

The following is a short morphological account of the organism thus isolated[1]. It is a large bacillus with rounded extremities, measuring 4 to 7 microns in length and 1 micron in breadth. The organism stains with the usual aniline dyes and is Gram positive. In liquid cultures, the bacilli appear in short chains of from 2 to 8 elements. The organism forms spores. Motility could not be detected, but flagella could be shown by Fontana's method, the flagella being peretrichous. Growth occurs in the usual media, nutrient agar, nutrient broth, etc., at a temperature of 60–65° C. No growth took place at 37° C. or at room temperature. Optimum growth was obtained under aerobic conditions, but the organism is a facultative anaerobe, as growth occurs in tubes of liver broth under paraffin.

The organism exhibited no growth on solid media under completely

[1] The writers are indebted to Mr R. E. Glover, B.Sc., M.R.C.V.S., and Mr R. L. Cornell, B Sc., M.R.C.V.S., of the Institute of Animal Pathology, Cambridge, for carrying out the examination of the morphological characteristics of the organism.

anaerobic conditions. It is non-proteolytic, tubes of meat broth and coagulated egg albumin showing no change after seven days' incubation. Colonies on agar appear after 24 hours' incubation. They are opaque, glistening white with dark centres and irregular edges, measuring 6 to 10 mm. in diameter.

The fermentation reactions were studied by adding a plain broth culture to peptone water containing 1 per cent. of the different sugars. Acid, but no gas, was produced with cane sugar, fructose, glucose, maltose, arabinose, mannite, inulin, dextrin and glycerol, no change occurring with lactose, dulcite, salicin or litmus milk. Indol was not produced in peptone water. So far, however, the sugar fermentations have not been carried out in cellulose media.

Experimental Part.

Exp. 1. 100 c.c. of tap water and the usual mixture of salts, together with 2 gm. of pulped filter paper, were introduced into a small flask, the customary precautions being taken. To the mixture was then added 5 c.c. of the active culture, and the flask was placed in a 65° C. incubator for 5 days, until the "head" which formed had completely disappeared. The contents of the flask were then filtered, and the filtrate, after concentration to a small bulk *in vacuo* at 45° C., was tested for the presence of reducing sugar by means of Fehling's reagent. A negative result was obtained.

The writers had occasion to repeat this experiment on numerous occasions. In every case the result was negative. Negative results were also obtained in similar experiments, when the contents of the flasks were tested for reducing sugar at intervals of 24 hours during the progress of the fermentation. If, therefore, sugar is formed as an intermediate product in the breakdown of cellulose, then it is, under the conditions of such tests, broken down very readily by the further activity of the bacteria, a behaviour which is quite in accordance with anticipation, since it had previously been shown that the organism is able to bring about a ready fermentation of glucose.

Exp. 2. A number of tests was now made in which the fermentation process was allowed to take place at 65° C. in collodion sacs, the latter being immersed in distilled water during the process. It had previously been ascertained that the organism was without action on collodion. The object of these tests was to discover whether it was possible to bring about a separation, by dialysis, of a portion of the sugar which might arise as a transient phase during the fermentation. The surround of

distilled water was renewed every 24 hours, and tests were made for reducing sugar in the water after its removal.

In only 3 out of 20 such tests were results of a positive nature obtained, the water surrounds removed after 3 days' incubation in the successful experiments displaying a slight reducing action towards Fehling's reagent. The unsatisfactory results in this series of tests may indicate that the rate of diffusion of sugar through the collodion membrane was appreciably slower than the rate of secondary fermentation of glucose. It must also be taken into account that the concentration of salts in the medium was altering continuously as a consequence of diffusion, and that this circumstance may have had a pronounced effect on the course of the fermentation. Nevertheless, it might be possible, by effecting improvements in technique, to obtain a more successful isolation of sugar by dialytic methods than was experienced in the present tests.

Exp. 3. To 10 gm. of pulped filter paper and 500 c.c. of the usual culture medium was added 15 c.c. of an active culture of the cellulose-splitting organisms. The flask and its contents were then placed in an incubator at 65° C. for 3 days. When the fermentation reaction was at its height, 40 c.c. of toluene was added with shaking. The flask was then placed in a 37° C. incubator for 5 days. At the end of this time the contents of the flask were filtered and evaporated to a small bulk *in vacuo* at 45° C. The concentrated liquid was then freed from separated salts by filtration.

The filtrate reduced Fehling's solution readily and copiously. When warmed in boiling water with phenylhydrazine and acetic acid, a copious yellow crystalline separation was effected from the hot solution in a few minutes. After continuing the heating in the water bath for 45 minutes, the crystallisation was allowed to proceed overnight at room temperature. The separated material was then filtered off, dissolved in hot dilute pyridine and the solution filtered. On cooling, crystals separated which had the beautiful characteristic appearance of glucosazone under the microscope.

It should be stated that this experiment was repeated time after time, always with the same positive result. Care was taken to ascertain whether any sugar other than glucose was present in the medium after filtration and concentration. In none of the tests with phenylhydrazine could any osazone other than that of glucose be detected.

Exp. 4. Four separate tests similar to that described under Exp. 3 were set going in the 65° C. incubator, this procedure involving the use of 40 gm. of pulped filter paper. Toluene was added in every case when

the reaction was at its height, and the flasks were then left for a further 5 days in the 37° C. incubator. The filtrates from the separate fermentations were combined and evaporated completely to dryness *in vacuo* at 45° C.

The dry residue was next extracted three times with boiling rectified spirit, and the filtered extract was reduced to about 25 c.c. by evaporation *in vacuo* at 45° C. The concentrated liquid reduced Fehling's solution with great readiness, and as little as three drops was sufficient to enable a characteristic specimen of glucosazone to be obtained.

The concentrated alcoholic extract was poured into a shallow glass vessel and the alcohol completely removed *in vacuo* at the ordinary temperature. The residue weighed 4·2 gm. and consisted of a stiff, caramel-like, hygroscopic mass, which displayed no tendency to become crystalline on standing for a fortnight in a desiccator. It possessed very strongly the powers of reducing Fehling's solution and of giving a characteristic glucosazone with phenylhydrazine and acetic acid.

Exp. 5. A sample of crude fibre was prepared from oat and tare silage by the orthodox method of acid and alkali treatment. The procedure described under Exp. 3 was then repeated, the crude fibre of the silage being used this time to replace the filter paper as a source of cellulose. There was again no difficulty in demonstrating the formation of glucose from the cellulose, the filtered solution, after concentration *in vacuo*, reducing Fehling's solution readily and yielding glucosazone with phenylhydrazine and acetic acid.

Comments on Exps. 3 and 4.

The results of these experiments demonstrate the possibility of obtaining glucose from cellulose by controlling the activity of cellulose-splitting organisms. At the stage of fermentation when toluene is added, no glucose is present in the medium (see Exps. 1 and 2). As the addition of toluene inhibits the further activity of living organisms, it must be presumed that the glucose which arises during the second stage of the fermentation is the result of the activity of enzymes which have been elaborated and secreted by the organisms during the first stage of the fermentation; or, alternatively, the addition of the antiseptic may lead to the liberation of such enzymes from an intracellular condition.

It appears necessary to assume therefore that the bacteria are unable to utilise directly, for metabolic purposes, the complex cellulose molecule, but must first cause this to be hydrolysed to the simpler form of glucose. This purpose is achieved by the agency of a cyto-hydrolytic enzyme

and, possibly, of other enzymes also, such as cellobiase. Here we appear to be dealing with a process of digestion comparable with that associated with higher organisms. Under normal conditions of fermentation, the glucose so formed would readily be assimilated and utilised by the micro-organisms for metabolic purposes, the end-products of such metabolism being organic acids and gases like methane and carbon dioxide. The addition of toluene, however, at the "head" stage of the fermentation rules out the possibility of any further metabolic activity of this character on the part of the organisms, so that any glucose formed in the second stage of the reaction by the continued activity of enzymes is enabled to escape destruction.

The results of Exps. 3 and 4 may be taken as deciding the main point at issue, namely, that glucose arises as an intermediate phase in the destructive fermentation of cellulose by bacterial agency. Although the writers have not so far devoted much attention to the quantitative aspects of the reaction, there can be no doubt that the yield of glucose under the conditions of these initial experiments is quite small. This, however, does not preclude the possibility of discovering conditions under which the yield of glucose might be increased considerably, in which case the reaction might conceivably acquire a technical significance, as, for instance, in the production of power alcohol. Once a reaction has been shown in the first place to be possible at all, it is frequently merely a question of studying in detail the various controlling factors in order to transform it from a low-yielding to a high-yielding process. The main object of this preliminary study, however, has been to test a point in theory rather than to secure results of an economic nature, and some time must necessarily elapse before the writers will be in a position to deal with the reaction from the quantitative and economic aspects. Meanwhile, it may be of interest to record some further observations which were made during the course of the work, since, although these are put forward somewhat tentatively at present, they nevertheless indicate the directions in which further investigations might profitably be pursued.

It was noted that the total amount of filter paper which was fermented away in the reaction was never anything like so considerable when toluene was added at the "head" stage as when the fermentation was allowed to proceed uncontrolled at 65° C. Under the last-named conditions, almost the whole of the filter paper underwent fermentation; under the conditions of toluene control, however, only 30–40 per cent. disappeared. Indeed, it appeared as if little or no further destruction of filter paper took place in the second stage of the fermentation after

the addition of toluene. It is possible, therefore, that the enzymes present in the second stage are concerned in producing glucose from partially hydrolysed cellulose, and that the primary cyto-hydrolytic process is dependent on the presence of the living organisms. This hypothesis, which would explain the low yields of glucose obtained in the reaction, would further account for the negative results, in respect of signs of fermentative activity and glucose formation, which were noted when filter paper was incubated with the liquid resulting from filtering a culture of the organisms at the "head" stage through a bacterial candle. On the other hand, however, it may be that a temperature of 37° C., at which the second stage of the incubation was carried out, is not the most favourable for the primary splitting of the cellulose complex by the cytase enzyme. In this connection, it will be recalled that attempts to grow the organism in the usual culture medium at 37° C. were unsuccessful. It may be also mentioned that the most successful experiment, in respect of glucose formation, in the present series was one in which the second stage was allowed to proceed at 65° C. instead of 37° C. Obviously the temperature factor is of considerable importance, and this phase of the question will be the object of further study.

Although negative results, in respect of glucose formation, were obtained in experiments in which the fermentation of filter paper was permitted to proceed unchecked at 65° C. until the "head" had disappeared, it was thought that, as the presence or absence of glucose at any given stage must depend on the relative rates at which it was being produced and destroyed in the two phases of the fermentative action, it might be possible under certain circumstances to detect the presence of traces of glucose in the culture without having recourse to the use of toluene. Several tests were carried out in which the fermentation at 65° C. was allowed to proceed to the "head" stage, at which time the flask was removed from the incubator and its contents examined, by the usual methods, for the presence of glucose.

As might be expected, the results obtained in such tests were not consistent. In one or two cases, however, the filtered and concentrated culture liquid displayed a faint reducing action towards Fehling's reagent, though whether this was due to traces of glucose, or to some other aldehydic substance, was not ascertained.

As it had not been found possible to grow the organism successfully at a temperature of 37° C., though this temperature had been found satisfactory for glucose formation in the toluene-controlled stage, there seemed grounds for believing that if the flask and its contents were

removed from the 65° C. incubator at the active "head" stage and placed in the 37° C. incubator, then the gas-producing mechanism of the organisms might be impaired or even put out of action, so that a portion at least of the glucose arising from continued enzymic activity might be saved from further breakdown. Again, however, the results obtained from tests of this character were indecisive, although in one or two instances, distinct signs of reducing power towards Fehling's solution were noted. One special set of observations is worthy of record on account of its possible significance. The filter paper fermentation was started at 65° C. in the usual way. The flask was removed at the "head" stage and, without addition of toluene, was kept for a further 24 hours at room temperature before proceeding with further tests. The contents were then filtered, and, after concentration *in vacuo*, were tested with Fehling's solution. A surprisingly strong reduction was noted, a result quite out of keeping with the observations in similar experiments, where the reducing action towards Fehling's solution had been, at best, quite faint. On enquiry, it was discovered that, during this particular fermentation, the temperature of the 65° C. incubator, by some mischance, had risen to 75° C. for a period of 12 hours. The influence of this higher temperature may therefore have led possibly to an enfeebling of the gas-producing mechanism, whilst not impairing the mechanism responsible for the production of glucose from the cellulose. The obvious line of enquiry suggested by this peculiar result will be followed up in future work.

Further experiments were undertaken with a view to finding out whether the organism was able to retain its power of fermenting cellulose after a period of sub-culturing in media devoid of cellulose. The organism was grown at 65° C. on a solid medium (plain agar) and, after 13 successive transfers on this medium, was introduced into peptone broth. After 8 successive transfers in the broth medium, 10 c.c. of the broth culture, representing sub-culture 21 in non-cellulose media at 65° C., was added in a flask to 2 grm. of pulped filter paper and 100 c.c. of the usual culture medium. The flask was then placed in the 65° C. incubator. No signs of any fermentative action were observed, even after the lapse of several days. It would appear therefore that continued sub-culturing of the organism in the absence of filter paper leads to a pronounced modification of its functional powers. It seems probable that this loss of cellulose-fermenting power is due to a gradual atrophy of the function which enables the organism, under normal circumstances, to produce glucose as a primary product from cellulose. If this be so, additional support is

given to the view that such cellulose-fermenting bacteria possess a dual mechanism, whereby, firstly, they hydrolyse cellulose to glucose, and secondly, ferment the glucose to organic acids and gases.

It has been demonstrated that when the fermentation of cellulose by bacteria is controlled by the addition of toluene at the "head" stage, this is followed by the appearance of small amounts of glucose. The main question remains to be settled, however, as to the nature of the mechanism which controls the bacterial action on digestible fibre in the rumen of the animal. Here the controlling factor is so efficient that something like 92 per cent. of the digestible cellulose becomes available to the animal in the form of glucose, and only about 8 per cent. undergoes complete fermentation to gases and organic acids. Surprise may be felt that so little of the glucose formed by bacterial action should undergo further breakdown; yet this is scarcely more surprising than that only about 8 per cent. of the digestible carbohydrate (starch, sugar, etc.) *originally* present in the food undergoes such destructive fermentation.

Further investigation will be necessary before the changes which occur in the rumen of the animal can receive adequate explanation. In the earlier paper (1), it was suggested that the extent of destructive fermentation of both cellulose and carbohydrate is determined by the energy requirements of the micro-organisms. On the other hand, if the primary conversion of cellulose into glucose is brought about by enzymes elaborated by the bacteria, there is no reason why this hydrolysis should be so regulated as to produce just sufficient, and no more, glucose as will satisfy the metabolic requirements of the micro-organisms. Bearing in mind the catalytic properties of enzymes, and their capacity for carrying out their functions independently of the living organism, it is not unreasonable to picture a continuous production of glucose from cellulose in the rumen quite irrespective of the limited requirements of the micro-organisms, which may be regarded solely, in this connection, as elaborators of the requisite enzymes. That glucose is actually formed from cellulose in the rumen on an *almost quantitative* scale is abundantly proved by Kellner's work on the fattening value of digestible fibre in the ruminant animal. The hypothesis put forward above as to how this occurs must, however, remain speculative until more supporting evidence has been obtained from work in artificial media than has been accumulated up to the present.

The possibility that the gas-producing activities of the micro-organisms may be circumscribed by the resulting increasing acidity of

the rumen contents is one which should also be kept in mind. Preliminary experiments conducted by the writers have indicated that small amounts of glucose may arise in the culture medium, when the latter is brought to a definite H ion concentration by the addition of acetic acid at the "head" stage of the fermentation. The writers hope to report more fully on this and other aspects of the subject at some future date.

REFERENCES.

(1) WOODMAN (1927). *J. Agric. Sci.* **17**, 333.
(2) PRINGSHEIM (1912). *Zeit. f. physiol. Chem.* **78**, 266.
(3) VILJOEN, FRED and PETERSON (1926). *J. Agric. Sci.* **16**, 1.

(*Received July 4th,* 1928.)

STUDIES IN SOIL CULTIVATION. IV.

A NEW FORM OF TRACTION DYNAMOMETER.

By W. B. HAINES and B. A. KEEN.

Soil Physics Department, Rothamsted Experimental Station.

(With Two Text-figures and Plates XII and XIII.)

Introduction.

In the first paper of this series (1) a description was given of the Watson dynamometer, which was employed for certain developments in the application of dynamometer technique to problems of soil cultivation, described in the second and third papers (2). For the continuation and extension of the experiments to different types of work it became very necessary to employ a dynamometer more adaptable than the original. This was designed for tractor ploughing, when the line of draught between tractor and plough was close to and fairly parallel with the ground surface. The higher and sloping line of draught employed in horse traction rendered the Watson dynamometer useless for extension to this kind of work, and in any case it was much too heavy for the purpose. It was also desirable to improve the method of recording the draught, which required constant and careful attention, especially in adverse conditions. A new dynamometer evolved to overcome these objections is described in the present paper. It is very light and portable, but of robust construction, and by a simple adjustment can be made to cover all ranges of draught from the heaviest to the lightest with the same percentage accuracy. The number of moving parts is very small and adjustments for stylus pressure, etc.—an inconvenient and frequent necessity with other instruments—are very rarely necessary. The system of recording employed is quite unaffected by weather or soil conditions. The apparatus has been very fully tested, and has been found very satisfactory. Its adaptability for different types of work is shown by its use at Rothamsted for horse ploughing investigations and, in India, for heavy mole drainage trials. It has been placed on the market by the Cambridge Instrument Company.

Description of the Dynamometer.

The dynamometer consists of three main parts: (*a*) a hydraulic link, in the form of a piston and cylinder containing oil, placed in the hitch of the implement; (*b*) the mechanism that records the fluctuations of

pressure on the oil as the implement is drawn forward; (*c*) control box, carried by the operator.

Copper tubing containing oil is used to transmit the pressure in the hydraulic link to the recording mechanism. The tubing is coiled in a spiral, so that alterations in the relative positions of link and recorder during work can occur without any strain on the apparatus. This arrangement also allows the recorder to be disposed in any convenient position.

The general arrangement of the constituent parts is shown in Pl. XII, fig. 1, and diagrammatically in Fig. 1. Referring to the figure, the hydraulic link *A*, is shown on the left. No serious disturbance is produced in the

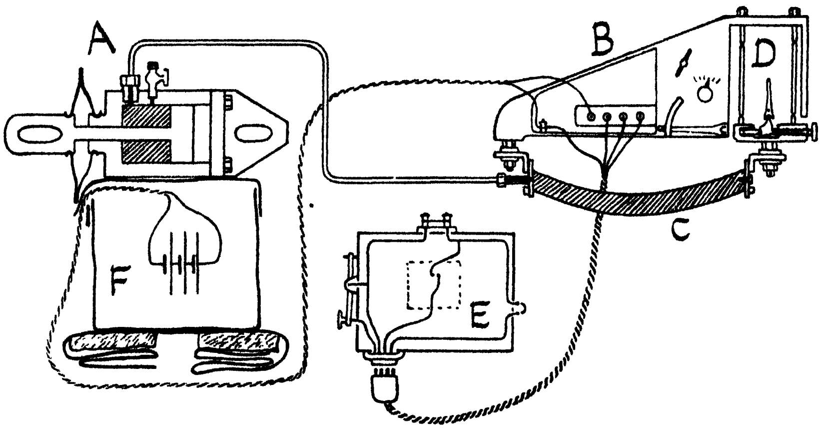


Fig. 1. The Rothamsted dynamometer in diagrammatic form.

line of draught when this is introduced into the hitch of an implement as its weight is only 16 lb., and the extra length entailed (about one foot) can, if necessary, be compensated by removing a few links from the hitch chain. A hollow leather collar is fixed over the end of the cylinder and the protruding portion of the piston, to prevent the entry of dust and water. The pressure is transmitted through the oil in the flexible copper tubing (not shown coiled in the diagram) to a Bourdon tube (*C*) also containing oil, and bent into the arc of a circle. The variations in oil pressure produce changes in the curvature of the arc, and in consequence, alterations in length of the chord. This change of length is very small, and is therefore directly proportional to the oil pressure, and thus to the soil resistance. The change of length is magnified and recorded by the mechanism *B* which is the well-known Stress Recorder manufactured by the Cambridge Instrument Company. The Bourdon tube is

rigidly bolted at its left-hand end to the frame of the Recorder, while the right-hand end is bolted to a floating stage. Three interchangeable Bourdon tubes are provided, of different strengths for use in light, medium and heavy work, respectively. The floating stage is supported by three steel pillars whose diameter is reduced at the points shown, to allow the stage to move to and fro in response to the extension and contraction of the Bourdon tube. This movement is magnified and transmitted to the recording arm *D* by a simple and robust system of two knife-edge levers. Attached to the upper portion of the arm is a very small rounded stylus, pressing against a celluloid ribbon 11 mm. wide that is advanced continuously by clockwork within the recorder casing. The speed of the clock can be varied within wide limits by turning an indicator on the recorder, and it can be started or stopped by an electrical control. The stylus does not scratch the celluloid, but causes it to flow plastically, so that the trace is impressed in the form of a grove bounded on each side by a small ridge. The line of zero draught can be adjusted by the small milled-head shown on the right of the floating stage, while the pressure of the stylus on the celluloid is adjusted, if necessary, by a second screw, not shown in Fig. 1. This method of recording has very great advantages, for the trace is permanent, and is unaffected by oil, dirt, or water. If necessary the celluloid ribbon can be cleaned by dipping it in water and wiping it dry with a cloth.

The small movement of the floating stage and the simple lever system of magnification result in the movement of the recording stylus being proportional to the stress applied to the hydraulic link. Direct calibration curves connecting stylus position and stress were obtained by suspending the link vertically, adding equal increments of weight up to the maximum, and then reducing the load by equal amounts to zero. The calibration curves for increasing and decreasing stress were linear, and identical.

In addition to the stress-recording stylus there are two others, that operate on the back of the ribbon, to avoid fouling the main stylus. One is used for recording time intervals and the other for position marks, and both are controlled electrically.

The three controlling circuits—clock for chart movements, time-recording clock, and position-recording key—are governed from the control box *E*, weighing only 4 lb., and carried in a light harness by the operator. The box carries (*a*) a switch for starting or stopping the chart, (*b*) a clock that momentarily closes, at ten second intervals, the circuit operating the time stylus, and (*c*) a tapping key for closing the circuit

operating the position stylus. The tapping key is used for recording position marks, passage from one plot to another, etc., and for marking on the chart in the Morse code any other details of importance. This feature is valuable: not only does it eliminate any possibility of confusion when the records of a complicated experiment are examined in the laboratory, but it also serves for recording important notes on the soil conditions, the behaviour of the implements, etc., that would otherwise have to be entered in a notebook while the experiment was actually in progress.

The three circuits have a common return wire, and are brought out to the four terminals of an ordinary wireless valve holder, so that a convenient and automatically correct connection can be made through a four-pin plug to the cables from the recorder. The cables are joined into one strand and lightly armoured for protection. The current for the circuits is provided by a six volt battery *F*, that can be carried in any convenient position. The low internal resistance type of dry battery is quite suitable for the purpose. In Fig. 1 and Pl. XII, fig. 1 they are shown in a leather case, riveted to a surcingle so that they may be carried on the back of the horse. For tractor ploughing the batteries would be carried on the tailboard, in which case they would be more conveniently connected to the two terminals shown on top of the control box.

A direct reading pressure dial gauge can be introduced if required into the oil system at any convenient point, or can be attached to the hydraulic link in place of the copper tubing and the recorder. Two such gauges, for heavy and light work respectively, and calibrated to give directly the pull applied to the hydraulic link, are shown as part of the dynamometer accessories in Pl. XII. Its main use is for purposes of demonstration, or for the securing of preliminary information. The limitations of a direct reading gauge as compared with a recording device are discussed later.

ASSEMBLY FOR FIELD WORK.

The method of assembly for field work is as follows. The hydraulic link is connected into the hitch, and the stress recorder, which weighs only 15 lb., is strapped in any convenient position on the implement, *e.g.* the beam of a plough, or the frame of a cultivator, care being taken to pad it with a roll of felt against mechanical shock, since the stylus responds to such vibrations. The Bourdon tube must also be unrestricted, and not liable to any casual contact with the implement. The link and the recorder are then connected by the spiral of copper tubing. This is

provided in fairly short lengths with screw unions so that it can be easily adapted to varying dispositions of the link and recorder. It is also necessary to tie down the tubing to some support at a short distance from each of the two ends, so that strains produced when turning at the headlands are not concentrated at these points but properly taken up in the spiral part of the tubing.

The whole system is then filled with oil from an oil-gun. The batteries are mounted, and if necessary the cables tied with string to suitable points to prevent them from dragging on the ground or fouling the implement. The operator then straps on the control box, inserts the four-pin plug into the socket and gives the signal for work to begin.

A photograph of the dynamometer in use for horse ploughing is reproduced in Pl. XII, fig. 2.

The operator walks beside the implement, using the tapping key to record on the chart the points of passage past pre-arranged points. For the general work, these points are previously fixed by stakes placed in the ground at suitable places. The tapping key is also used, as previously mentioned, for Morse code notes of the work.

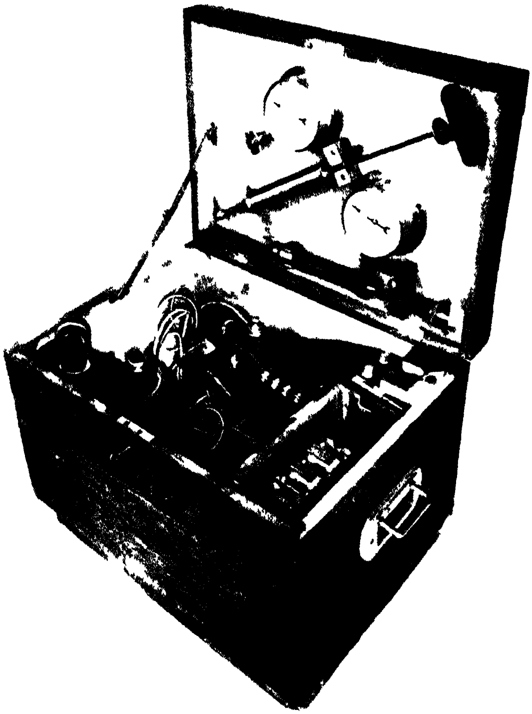
The celluloid ribbon passes out through a slot in the recorder, and convenient lengths of it can be cut off at intervals. A low power microscope is provided in the kit, so that the record can be examined in detail to check the correct functioning of the recorder. The portability of the complete equipment may be judged from Pl. XIII, showing it packed for transit, in a strong oak box, of outside dimensions $21 \times 15 \times 14$ in. The total weight, including spare oil, tool bag (carried in the box but not shown in the photograph) is under 100 lb.

Laboratory Examination of the Records.

The examination and reduction of the records is done in the laboratory. The trace is too small for direct integration, so this process must be carried out on enlarged copies. The optical properties of the groove and flanking ridges that constitute the actual trace on the celluloid give rise to a very clear and sharp magnified image, that can be taken on sensitive paper, or copied by hand. In many uses of the Stress Recorder, requiring an intensive examination of the stresses during a short interval, the photographic method of enlargement has been found best. But the nature of the problem in soil resistance measurements is quite different. Although minor fluctuations in resistance can be recorded with great fidelity, their exact significance refers primarily to the occurrence of stones in the soil, to the gait of the horses and other casual factors,

Fig. 1 The Rothamsted dynamometer, showing the units assembled.

Fig. 2. The dynamometer as arranged for horse-ploughing measurements.



Showing dynamometer and accessories packed for transport Total weight less than 100 lb

whereas the present interest of the results for soil research lies in the mean values of soil resistance obtained from extended records.

The method we have adopted is to use a low power microscope and camera lucida to transfer an enlarged image ($\times$ 34) of the trace to paper, after which it can be divided into its sections as shown by the position marks, and the mean stress of each section calculated by integrating the area with a planimeter, and applying the linear calibration factor. The chart is fed, a step at a time, between two glass plates, mounted a short distance apart, that serve to keep it flat and retain it in position.

With the ribbon speed employed in horse work it is possible to get two adjacent sections of the trace, each representing about twenty-two yards of ploughing, into the field of view at the same time.

THE CHARACTER OF THE RECORD UNDER DIFFERENT CONDITIONS.

The whole question of the amount of detail to record in the stress fluctuations either on the trace itself, or in the enlarged copy, requires some judgment to obtain the best results. The instrument is capable of recording stress fluctuations in full detail, if filled with thin oil, and run with a chart speed high enough to open out the trace. Conversely the fluctuations in the record may be smoothed or damped out to any required extent by the use of thick oil, and by introducing a needle valve constriction in the copper tubing. Damping, however, makes the instrument sluggish, and when it was carried to the point of smoothing out all minor fluctuations, the time lag introduced between the application of the stress at the link and the complete response of the recorder was found to be twenty seconds For horse work this corresponds to a distance of twenty yards or more, and the position marks impressed on the chart would refer, not to the part of the soil resistance trace immediately above them, but to a part some indefinite distance along the trace.

The details of the trace are also obscured if the record is condensed by using a slow chart speed, yet a reasonably condensed record is desirable for enlargement, since the field of the microscope then covers a good portion of the work. With a little experience a good compromise between these opposing requirements can be secured. In general a chart speed of about 1/4000 that of the implement gives good results. This is equivalent to one yard of chart for each two and a half miles travel of the implement. In horse ploughing this relation implies a chart speed of about 0·6 in. or 15 mm. per minute. With tractor or steam power implements, a faster chart speed is needed. For the dimensions of the copper tubing usually employed (length about 150 cm., internal diameter

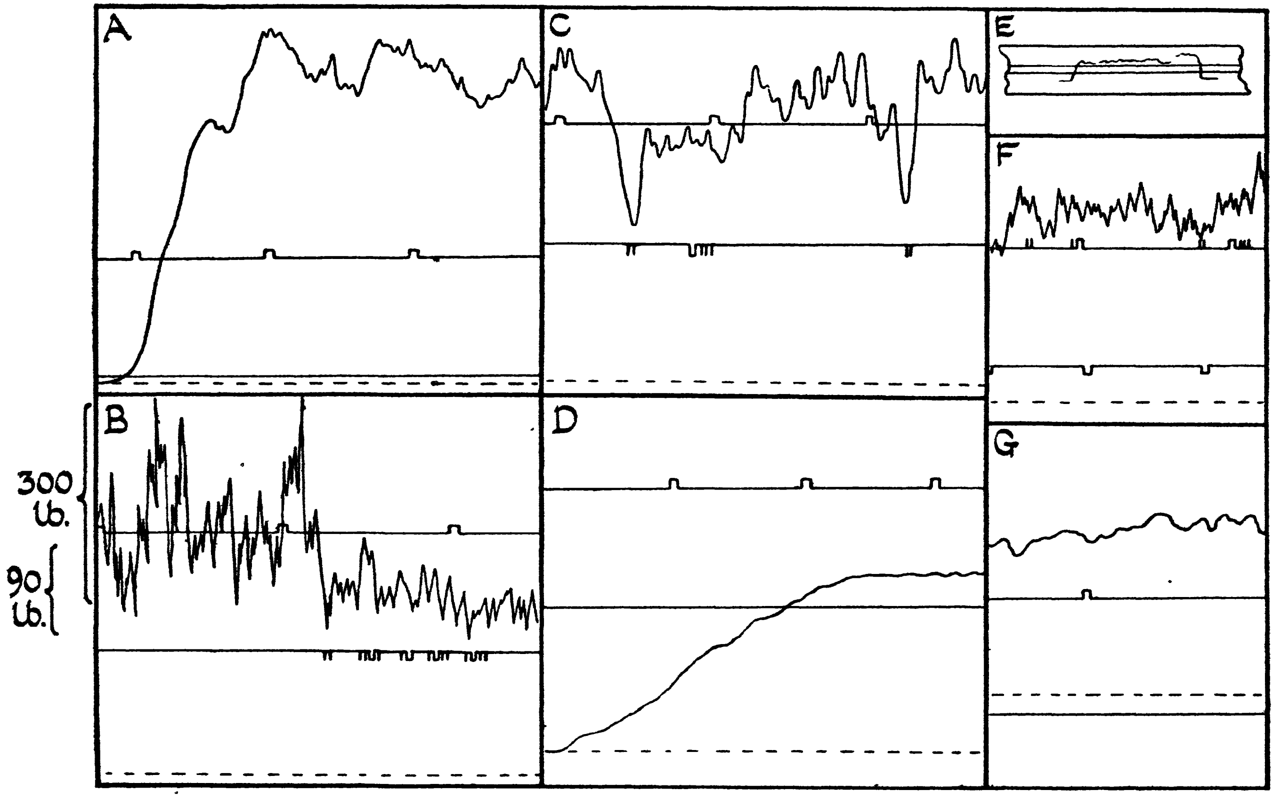


Fig. 2. Enlarged facsimiles of different types of trace: horse ploughing.

4 mm.), an ordinary engine lubricating oil is quite suitable for the pressure system in winter, but it is desirable to thicken it with gear oil in the warmer months.

The above remarks are illustrated by Fig. 2, showing different types of trace obtained with a horse plough. They are facsimile reproductions obtained with microscope and camera lucida as already described. As reproduced in Fig. 2 the magnification is about 10 diameters; a piece of the original trace is reproduced at *E* to the same scale, for comparison. In each of the enlarged traces the dotted line shows the position of the line of zero draught. The two straight full lines are the time and position scales.

The effect of damping is shown in a comparison of traces *A*, *B* and *D*, that refer respectively to normal, insufficient, and excessive damping. Trace *B* was obtained with thin oil and in warm weather; the record is characterised by many sharp changes in direction of the stylus movement, as it follows the abrupt changes in soil resistance. Trace *A* shows a normal amount of damping. The amplitude of the short period fluctuations is somewhat reduced and the sharp points are now somewhat rounded. A trace of this type is much easier to integrate with a planimeter than trace *B*, while the contribution to the total area of the areas within the sharp peaks is so small that their omission is unimportant. The time lag corresponding to trace *A* is not too large, as may be seen by the quick rise of the trace from the zero-draught line when the plough enters its work. Trace *D* shows excessive damping. The minor fluctuations have largely disappeared, and the trace takes about 20 sec. (two marks on the time scale) to rise to its full value.

The effect of the type of work itself on the character of the record is illustrated in traces *F*, *G*, *C* and *B*.

Trace *F* is a typical record on Rothamsted soil, a heavy loam with numerous flints, and shows the jerky "harsh" nature of the pull; trace *G* shows the much smoother pull characteristic of the Woburn sandy soil. Trace *C* is a record of work on Rothamsted soil with a ridging plough that was used in the early spring to break up old weathered furrows, containing much turf. It shows large fluctuations due to the uneven nature of the work, but the record is much more rounded than that in trace *F*. This is due to masses of turf acting as semi-plastic pads or buffers to the motion of the implement through the soil, and in consequence smoothing out the rapid fluctuations in pull. Trace *C* also demonstrates the use of the position marks for the indentification of particular portions of the record. Two such marks (each consisting of a double dot) are shown, specifying the beginning and end of plot *B*, that

is indicated in the Morse code (–···). The position marks referred to the passage across the open furrows of the former ploughing; the drop in draught as the plough crosses these trenches is well shown, and the absence of any time lag is also demonstrated.

Trace *B* further illustrates the relation between the nature of the work and the type of record. The record falls obviously into two sections separated by the position mark (··), that represents the boundary between a stubble badly infested with couch grass (on the left), and a fallow, well cultivated portion (on the right). The latter is marked in Morse code with the first four letters of the word "fallow." On the stubble section the matted grass and clods of soil obstructed the plough, causing wide and erratic fluctuations in pull, covering a range of about 300 lb., which, by reference to the zero-draught line, is seen to represent over half the average value. On passing to the fallow portion, the implement travels normally, and the fluctuations at once settle down to the much smaller range of about 90 lb.

The Limitations of a Direct-reading Dynamometer.

The question whether the addition of a recording instrument could be avoided by taking the readings direct from the pressure-gauge attachment, can now be considered in the light of the above discussion.

It is evident, for the type of investigation dealt with in this series of papers, that it would be quite impossible to take accurate readings from a pointer that is rapidly fluctuating over half its total range, and even if this were possible the readings could not be taken down rapidly enough to secure a good mean for small-sized plots. Quite apart from this, the noting of position marks, speed of work, and other details would necessitate at least one extra observer and very practised and efficient co-operation if the results were to be reliable. Any method of damping the fluctuations sufficiently to make direct reading possible, quite spoils the coincidence between recorded draw bar pull and field position. There appears no escape from the conclusion that integrated records of a self-recording instrument are essential for reliable results, although for simple field demonstrations over a large area, a direct reading implement with heavy damping can usefully be employed.

Summary.

A new and improved type of dynamometer is described which by a simple interchange of parts can be used with the same percentage accuracy for all types of work from the lightest to the heaviest.

The instrument consists of (*a*) an hydraulic link weighing 16 lb. and placed in the hitch, (*b*) a recording mechanism weighing 15 lb. carried on any convenient part of the implement, and (*c*) a control box weighing 4 lb. carried by the operator. When packed in a stout box for transit and with all accessories the total weight is less than 100 lb. The instrument is of robust construction and has a minimum number of moving parts. Adjustments for stylus pressure, etc., are provided, but the necessity for using them hardly ever arises.

The instrument operates by recording the amount of movement in a Bourdon tube filled with oil and connected by narrow bore copper tubing to the oil in the hydraulic link.

The recording mechanism has been adapted from the Cambridge Instrument Company's Stress Recorder. The trace is impressed on a narrow, moving celluloid ribbon, and is permanent, and also unaffected by water, oil, or dirt. The optical properties of the trace give a clear and sharp magnified image, which can be traced by hand or photographed for purposes of integration. The construction of the instrument is such that the movement of the recording stylus is directly proportional to the stress applied to the hydraulic link.

In addition to this record of draught two other records, operated electromagnetically, are impressed on the ribbon: (*a*) a time trace showing a mark for each ten seconds, and (*b*) a position trace on which the passage from one plot to another is marked, and on which any field notes or other details are impressed in the Morse code by means of a tapping key carried by the operator. The styluses for these two records operate on the back of the ribbon so that the motion of the stylus recording the draught is unobstructed.

The method of magnifying the charts for integration with a planimeter is described, and typical records are reproduced, showing the character of the trace for different types of work, and the relation between the amount of detail on the trace and the degree of damping introduced into the oil system.

REFERENCES.

(1) KEEN and HAINES (1925). *J. Agric. Sci.* **15**, 375–386. (Rothamsted Memoirs, **12.**)

(2) HAINES and KEEN (1925). *J. Agric. Sci.* **15**, 387–394; 395–406. (Rothamsted Memoirs, **12.**)

(*Received July* 17*th*, 1928.)

THE REVISED OFFICIAL BRITISH METHOD FOR MECHANICAL ANALYSIS.

By A SUB-COMMITTEE[1] OF THE AGRICULTURAL EDUCATION ASSOCIATION.

In a former number of this *Journal* (1), there appeared a report on the mechanical analysis of soils by this sub-committee of the Agricultural Education Association. The report contained proposals for certain modifications of the earlier A.E.A. (1906) method, of which the most important were the introduction of hydrogen peroxide as a dispersive agent in the preliminary treatment, the use of the pipette method for the actual mechanical analysis, and the abolition of the fine gravel (3 mm.–1 mm.) fraction. This report was officially adopted by the A.E.A. and the method of mechanical analysis therein proposed was accepted as the new standard to replace the 1906 method. The full details were published in the *Journal* of the Association (2).

In the present report we give an account of certain developments that in our opinion made it very desirable for further modifications to be introduced in the official method. These changes have in fact been accepted by the A.E.A. and the revised method of mechanical analysis has already been published (3).

The same considerations which had led to a review of methods of mechanical analysis in this country also led to the problem being attacked by the International Society of Soil Science. A beginning of international effort in this direction was made in connection with the Soil Congress at Rome in 1924, where plans were made for further co-operative investigation. These investigations, in which some twenty workers in different lands participated, were considered at a special meeting of the 1st Commission at Rothamsted in October 1926. It had already been demonstrated that the pipette method of analysis gave results in complete agreement with the older and less convenient direct sedimentation methods and the principal problems before the Commission were (*a*) the method of dispersion to be adopted and (*b*) the grouping of fractions, and the expression of results. With regard to the first question, it was recommended that for scientific as opposed to purely technical purposes, the preliminary dispersion should be effected by means of hydrogen peroxide, hydrochloric acid, and aqueous ammonia, as in the A.E.A.

[1] Consisting of Prof. N. M. Comber, Dr B. Dyer, Prof. J. Hendrick, Prof. G. W. Robinson, Mr T. Wallace and Dr B. A. Keen, Convener.

method. With regard to the second question, the preponderance of opinion was in favour of the well-known and widely used Atterberg scale, in which the successive particle size limits are 0·002–0·02–0·2–2·0 mm. It was decided that this scale should be adopted, but that precision should be given to its significance by standardising the correspondence between particle sizes and settling velocities, since the actual separation is effected on the latter basis. It was also recommended that the standard temperature should be 20° C. and that, where necessary, corrections should be applied for the variations in the viscosity of water at different temperatures. The Commission were unable to agree with the British system of expressing the fractions on the ignited basis, and concluded in favour of expressing the fractions as oven dry at 100–105° C. which is the system in use in practically all countries, except Great Britain and some of the Dominions and Colonies.

The recommendations of the Commission were fully considered at the International Soil Congress at Washington in 1927. The proposals concerning dispersion were approved, and it is worthy of mention that the British practice has thus secured international recognition.

With regard to the grouping of the fractions, some discussion had taken place since the Rothamsted meeting, with the result that a modified proposal was put forward and adopted. This proposal was to the effect that the Atterberg scale of particle sizes should be used, but that instead of using the Atterberg settling velocities without modification, the particle size and settling velocity for clay on the Atterberg scale should be taken as the datum and other settling velocities calculated, assuming Stokes' Law to hold good. The scale thus adopted is as follows:

Fraction	Particle size mm.		Settling depth and velocity time
Clay	0·002		10 cm. in 8 hr.
Silt	0·02		10 cm. in 4 min. 48 sec.
Fine sand	0·2	separated by sieves	(10 cm. in 2·88 sec.)
Coarse sand	2·0		

It will be seen that there are only four fractions in the new scale, two of which are obtained by pipette sampling.

The standard temperature is to be 20° C. and where analyses are conducted at different temperatures, appropriate corrections are to be applied for changes in the viscosity of water. The recommendations of the Rothamsted meeting as to expressing the fractions on oven-dried basis were confirmed.

The decisions of the Washington Congress were considered by the Chemistry Committee of the A.E.A. in December 1927. After full

discussion it was unanimously decided to adopt the international method, with the single difference that the percentage of moisture in the air-dry soil should also be included as part of the determination, as it was felt that in our conditions this figure was of value. Another consideration was that with certain soils the preliminary drying to 105° C. in the International method might lead to difficulties in the dispersion, a point of obvious importance in the pipette technique.

The retention of the air-dry moisture figure does not destroy the essential unity of the International and British methods, since it can be eliminated from the results by a simple arithmetical transformation.

The Committee fully realised the gravity of the step, and the inconvenience caused by a further change following so soon on the adoption of the 1925 method, but the ultimate advantages will be so strong that the reasons for the change were overwhelming. The essential features of the British method appear in the International method, and if any change at all were to be made in the British 1925 method, it was highly desirable that they should be made as soon as possible before any large number of analyses had accumulated. Although these were important points, the fundamental reasons for the change were the recognition of the international scope of soil studies and of the advantage to be gained by British workers from the practical identity between the International and British official methods.

It will be observed that the changes are principally in the substitutions of oven dry for ignited weights and in the number and dimensions of the fractions. The former is the more serious but it has to be recognised that the oven-dry basis is already standard practice for most countries, and that the main reason for its introduction in the 1906 method—removal of organic matter from the fractions before weighing—was rendered nugatory by the introduction of the peroxide pretreatment. There is also the further point that the "loss on ignition" figure of the whole soil is no trustworthy indication of the amount of organic matter present. Nevertheless, for some time to come it will be necessary for British workers to determine both the oven dry and ignited weights of the fractions and to use the summation percentage curve procedure whenever they desire to compare the mechanical analysis of a soil under the new method with earlier results.

The change in the number and size of the fraction is relatively unimportant. The use of the summation percentage curve for transferring the results on one scale to any other with little or no loss of accuracy has been referred to in our earlier report.

The size of the round holed sieve used for preparing the soil sample is increased from 1·0 mm. to 2·0 mm. The 0·2 mm. sieve is retained. Attention is drawn to the definite specification of this sieve in the Revised British Method, as there has been some confusion in the past. The specification of the Institute of Mining and Metallurgy has been adopted, and No. 70, I.M.M. sieve has been selected as the nearest standard to the 0·2 mm. dimension. This is a woven wire sieve, the diameter of the wire and the length of one side of the square hole being equal to each other. There are 70 cm. to the linear inch, so that the width of the hole is 1/140 in. or 0·181 mm. The variation in aperture sizes owing to the difficulty of weaving uniform sieves, and the fact that the sieves stretch slightly in use, render unnecessary any attempt to get closer to the theoretical value. The most striking alteration is in the clay fraction, whose settling velocity has been changed from 8·6 cm. in 24 hours at 15° C. (or 9·8 cm. in 24 hours at 20° C.) to 10 cm. in 8 hours at 20° C., *i.e.* over three times its original value. This alteration however has relatively little effect in increasing the percentage of the fraction even in heavy soils; hence those who are accustomed to use the results of a mechanical analysis for estimating the texture of a soil in the field should not be inconvenienced by this part of the change, although they must remember that the actual percentage of the fraction is still further increased owing to the employment of an oven dried and not ignited basis.

The details of the new method so far as they differ from the earlier (1925) method are given in the appendix.

REFERENCES.

(1) Sub-Committee of the Agricultural Education Association. The Mechanical Analysis of Soils: A Report on the Present Position, and Recommendations for a New Official Method. *J. Agric. Sci.* (1926), **16**, 123–44. (Rothamsted Memoirs, **13**.)

(2) Sub-Committee of the Agricultural Education Association. The Official Method for the Mechanical Analysis of Soils. Adopted by the Agricultural Education Association in 1925. *Agricultural Progress* (1926), **3**, 106–10.

(3) Sub-Committee of the Agricultural Education Association. Revised Official Method for the Mechanical Analysis of Soils. Adopted by the Agricultural Education Association in 1927. *Agricultural Progress* (1928), **5**, 137–44.

APPENDIX.

The full details of the new method are given in *Agricultural Progress*, 1928 (ref. 3). Reprints are available and may be obtained, price 3*d.*, from the Secretary of the A.E.A., Mr H. H. Nicholson, Department of Agriculture, The University, Reading.

Preparation of the sample. As before, except that a 2·0 mm. sieve is used in place of the 1 mm. sieve of the 1925 method.

Dispersion, determination of loss by solution, and coarse sand. As in 1925 method, except that the coarse sand is dried at 105° C. The ignited weight can be obtained, subsequent to weighing after drying.

Determination of silt, and clay. The material passing the 0·2 mm. sieve is shaken with ammoniacal water (1 per cent. ammonia) as before and the suspension made up to 1 litre in a cylinder. The suspension, after being well shaken by repeated inversion of the cylinder, is allowed to stand for 4 minutes 48 seconds and is sampled at 10 cm. Different depths and times may be used, provided the same depth/time ratio is used. The tared dish containing the suspension is dried at 105° C. and, after being cooled, weighed. From the weight of the dry matter, the percentage of silt plus clay is calculated. If desired the dish and residue may be ignited and weighed, to obtain the ignited figures.

The contents of the cylinder are again shaken for about a minute by repeated inversion and allowed to stand for 8 hours, after which period, sampling is made at 10 cm. below the new level. The percentage of clay is obtained after drying the sample of suspension at 105° C. The difference from the figure obtained by the first sampling gives the percentage of silt. The clay may also be ignited after drying if thus desired.

Determination of fine sand. The bulk of the supernatant suspension in the cylinder, from which the fine sand has settled out, is now poured away, and the remainder, together with the sediment, is washed into a 400 c.c. beaker. Repeated sedimentations using a depth of 10 cm. and time 4 min. 48 sec. removes the finer fractions and the fine sand is left in the beaker, from which it is collected, dried and weighed. Here, again, the ignited figures can be obtained if desired.

Note. As the first sampling is at 10 cm., instead of 30 cm. as in the earlier method, there is no necessity to make a litre of 2 per cent. suspension. It is permissible to use 10 gm. of soil, and make up the suspension in a 500 c.c. cylinder. Probably, however, the greater diameter of the litre cylinder permits more accurate sampling.

Mechanical analysis by the sedimentation method. As in the earlier 1925 method, but with the use of the new depth/time ratios.

Determination of carbonates. As before.

Moisture content in air-dry sample. As before. Where ignited results are also desired, the loss on ignition may be determined after oven drying.

Statement of results. The statement of results will be explained by the following example, which gives the figures for a Pennant Grit soil from Glamorganshire. Figures on the ignited basis are also given for comparison.

Revised official method	
Coarse sand	22·3
Fine sand	32·7
Silt	18·2
Clay	16·8
Moisture in air-dry sample	3·1
Carbonates	0·7
Solution loss	1·8
Difference	4·4
	100·0

Ignited basis	
Coarse sand	21·7
Fine sand	32·3
Silt	18·7
Clay	14·0
Moisture	3·1
Loss on ignition	8·6
Carbonates	0·7
Loss by solution	1·8
Difference	−0·9
	100·0

The results on the Revised Official method are converted to the International system by leaving out the air-dry moisture figure and raising all the other items in the ratio 100/(100 − 3·1).

As already stated, in the Revised Official Method, "loss on ignition" does not appear. The difference from 100 consists principally of the humified organic matter (about 80 per cent. of the total) dissolved or destroyed by peroxide treatment. But as the figure is also charged with analytical errors, it cannot be recommended as a measure of the organic matter present. A trustworthy and convenient method for the determination of organic matter is greatly to be desired.

Correction for temperature. If at 20° C. the depth of sampling is 10 cm. then in order to correct for the changes in viscosity of water with temperature, the following depths must be used at different temperatures.

Temperature (deg. C.)	5	10	15	20	25	30
Depth (cm.)	6·6	7·8	8·8	10·0	11·25	12·6

(*Received July 17th*, 1928.)

"SINGLE VALUE" SOIL PROPERTIES: A STUDY OF THE SIGNIFICANCE OF CERTAIN SOIL CONSTANTS.

By B. A. KEEN and J. R. H. COUTTS.
Soil Physics Department, Rothamsted Experimental Station.

(With Four Text-figures.)

CONTENTS.

1. Introduction.

Attempts have been made by many workers to assess the general character of a soil by measuring one property (or one group of properties) thus specifying the soil by a single number, in place of the group of figures obtained from a detailed mechanical analysis. Such measurements will be referred to in this paper as "single value" determinations.

At present there is no accepted standard physical specification of soil except its mechanical analysis by some recognised method, and this is not a single value function. Although useful information can be extracted from the mechanical analysis as to the probable field behaviour of the soil and its general characteristics, the conclusions are not quantitative or absolute: a good deal of personal judgment, based on previous experience, must be exercised in the interpretations, and, to add to the difficulty, many so-called standard methods do not secure complete disintegration of the soil aggregates. The use of hydrogen peroxide, introduced by Robinson (1), and now adopted in the British (2) and International methods (3), has removed the latter difficulty, but Odén's (4) noteworthy attempt to express mechanical composition as a continuous function of particle size has not, as yet, overcome the serious inherent

experimental error detected by Coutts and Crowther (5). It is therefore still necessary to express the results of a mechanical analysis as a limited number of groups of particles having specified diameter limits, and this is a crude and unsatisfactory basis for a standard physical specification.

Numerous attempts have been made to use some single value basis of specification. They have been based either on the measurement of moisture content or moisture relationships under defined experimental conditions, or on the colloidal properties of the soil. The hygroscopic coefficient, moisture equivalent, and wilting coefficient, due largely to Briggs and his associates, are among the well-known examples of the former class whose significance has already been discussed by one of us (6). To these may be added, as typical later examples, the rate of evaporation at a given moisture content (7), and the so-called "suction-force" of the soil for water (8).

Measurements depending more or less on the colloidal properties of the soil are its power of dye absorption (9), the heat of wetting (10), the shrinkage of a kneaded block of moist soil (11), and the "sticky point," defined as the moisture content at which kneaded moist soil just ceases to adhere to external objects (12).

There are objections to the use of some of the above determinations as single value constants.

The hygroscopic coefficient is an unsound conception, and the values customarily reported are not equilibrium values at all (13). The wilting coefficient was shown by the work of Alway (14) and Shull (15) to be a complex determination into which the soil, the plant, and the atmospheric conditions all enter.

In spite of certain empirical details the moisture equivalent has attractions as a single value measurement; Cameron and Gallagher (16) showed that it was approximately equal to the practical "optimum moisture content" for plant growth, and more recently Shaw (17) has shown that the equilibrium moisture content in irrigated soil where no ground water table exists is also equal to the moisture equivalent. The fact that few soil laboratories can afford the cost of the apparatus led us to exclude this determination from our present investigation.

The rate of evaporation at a given moisture content is not a suitable measurement, for recent critical examination (18) shows that extreme care is required to obtain reproducible results, and in any case they are difficult to interpret. The work of Haines (19) and R. A. Fisher (20) has elucidated the true nature of the so-called "suction-force," and it is evident that it will not serve for our present purpose.

As originally introduced, measurement of dye absorption was based on the theory of a simple physical adsorption, with the idea that comparisons of effective particle surface between different soils would be possible; this concept has long since been abandoned. The same idea is implicit in the heat of wetting determination; Bouyoucos (10 *b*) and other workers have devoted much attention to this measurement, which has some attractive features. However, the results of some work at Rothamsted, at present unpublished, led us to exclude it, for the time being, from our list of suitable methods.

The shrinkage of a plastic block, and the sticky point measurement were included in our investigations and are discussed below.

2. Scope of the Present Investigation.

The single values selected for study were those that could be measured with simple apparatus, and which were either known to be measuring some definite soil characteristic or seemed to offer promise of doing so.

The determinations made were as follows:

Percentage of clay fraction[1] (C).
Moisture content of air-dry soil (A).
Moisture content in equilibrium with atmosphere of 50 per cent. relative humidity (R).
Loss on ignition of dry soil (I).
Moisture content at sticky point (S).

Haines' method for volume shrinkage (11 *c*) was also used to obtain the following derived quantities:

Moisture content of saturated block (m).
Pore space of oven-dried block (P).
Apparent specific gravity of block (σ).
True specific gravity of block (ρ).

Where necessary the suffixes o and p are used to distinguish between values for original soils and those treated with hydrogen peroxide as described immediately below.

The percentage of calcium carbonate in the soils was also determined.

A number of other measurements were made which are referred to in the body of the paper.

[1] The experiments were completed before the Revised British Official Method of Mechanical Analysis (*Agricultural Progress* (2 *c*)) was adopted. The clay figures are those obtained by the earlier method (*Agricultural Progress* (2 *b*)). The values for the clay content given in this paper are therefore less than they would have been with the new method, but the differences are relatively small and do not appreciably affect any of the conclusions that have been drawn.

The most important feature of the present investigation, apart from the careful selection of suitable single value determinations, was the repetition of the measurements after the soils had been treated with hydrogen peroxide. It is evident that both organic matter and the mineral part of the soil are concerned to varying degrees in all single value measurements, and until recently there has been no experimental means of separately assessing the effects. For this purpose the use of hydrogen peroxide appeared well worthy of extended trial, since, in any single value determination, the difference in results for the original soil and the peroxide treated soil would give a direct indication of the contribution of the organic matter to the value. This implies, however, that the peroxide is without effect on the mineral portion of the soil. The assumption is not strictly true: a small amount of mineral material is dissolved that comes principally from the clay fraction and consists of mixed sesquioxide and a small quantity of silica (2 *a*). It is not yet definitely known whether the removal of this material appreciably alters the physical and physico-chemical properties of the mineral portion of the soil, but the available evidence is rather against this possibility.

In the present investigations, therefore, it has been assumed that peroxide has removed humified organic material without affecting the physical properties of the mineral part of the soil.

3. THE SOILS USED.

In all, 39 soils were subjected to the complete set of measurements outlined above, both on original and peroxide treated samples. The soils selected showed a wide range of type and properties, varying from heavy clays to light sands, a number of samples from depths below the top soil were also included, together with certain Rothamsted and Woburn soils that differed widely in manurial treatment.

Prior to the experiments all the soils were air dried and passed through a 1 mm. sieve with round holes.

Table I gives a descriptive list of the soils employed, which are top soils unless otherwise stated.

4. DESCRIPTION OF METHODS.

Percentage of clay (C). This was determined on the old basis for this fraction (settling velocity 8·6 cm. in 24 hours at 15° C.) in the usual way.

Air-dry moisture content (A), *moisture at* 50 *per cent. relative humidity* (R) *and loss on ignition* (I). The air-dry moisture content was determined in the ordinary way, the soil being heated 24 hours in a steam oven.

Table I. *List of soils used.*

Soil No.	Locality	Type
1	Cwybr Fawr, Rhyl, Wales, F. 86	Sandy loam, Triassic drift
2	Chwaen Goch, Llanerchymedd, Anglesey, Wales, A. 132	Silt loam, Ordovician shales
3	Garforth, Yorks, 34	Clay loam, Coal measures
4	Garforth, Yorks, 113	Light loam, Coal measures
5	Woburn, Stackyard Field. Unmanured	Light sand, Lower greensand
6	Woburn, Stackyard Field. Farmyard manure	Light sand, Lower greensand
7	Rothamsted, Hoosfield Fallow. 9–18 in.	Heavy loam. Subsoil, Clay with flints
8	Rothamsted, Hoosfield Wheat. 9–13½ in.	Heavy loam. Subsoil, Clay with flints
9	Rothamsted, Barnfield. Farmyard manure. 0–9 in.	Heavy loam. Subsoil, Clay with flints
10	Rothamsted, Sawyers Field	Heavy loam. Clay with flints
11	Melchet Court	Sandy soil
12	Craibstone, Aberdeen	Light sand. Limed, Granitic drift
13	Craibstone, Aberdeen	Light sand. Unlimed, Granitic drift
14	Craibstone, Aberdeen	Light sand. Limed subsoil, granitic drift
15	Craibstone, Aberdeen	Light sand. Unlimed subsoil, Granitic drift
16	Vaynol, near Bangor, Wales	Raw subsoil. Heavy Carboniferous Limestone clay
17	Deep excavation in Oxford Street, London	London clay
18	Wad Medani, Sudan	Gezira soil (badobe)
19	Mikveh, Palestine	"Argileuze" (0–30 cm.)
20	Harpenden Common	Clay with flints
21	—	Kaolin (B.D.H. purified)
22	Dagenham, Essex. 107	Recent gravel
23	Dagenham, Essex. 107	Subsoil, recent gravel
24	White Roding, Essex. 72	Boulder clay
25	White Roding, Essex. 72	Subsoil, Boulder clay
26	Abbess Roding, Essex. 73	Boulder clay
27	Abbess Roding, Essex. 73	Subsoil, Boulder clay
28	Thundersley, Essex. 117	Bagshot
29	Thundersley, Essex. 117	Subsoil, Bagshot
30	Rochford, Essex. 127	Brickearth
31	Rochford, Essex. 127	Subsoil, Brickearth
32	Ardleigh, Essex. 162	Glacial loam
33	Ardleigh, Essex. 162	Subsoil, Glacial loam
34	Beaumont-cum-Moze, Essex. 172	Alluvium
35	Beaumont-cum-Moze, Essex. 172	Subsoil, Alluvium
36	St Osyth, Essex. 177	Marsh alluvium
37	St Osyth, Essex. 177	Subsoil, Marsh alluvium
38	Gt Wigborough, Essex. 183	London clay
39	Gt Wigborough, Essex. 183	Subsoil, London clay

The moisture content at 50 per cent. relative humidity was determined as follows:

About 10 gm. of the air-dry soil were placed in a squat weighing bottle and exposed over sulphuric acid (density 1·3325 at 15° C.) in a vacuum desiccator kept in a dark room at approximately constant temperature. Equilibrium was assumed to be reached when the weight did not change by more than 1 mgm. in 2 days. The weighing bottles were then transferred to a second vacuum desiccator containing concentrated sulphuric acid and allowed to reach equilibrium as before.

A portion of this dried soil was transferred to a silica basin, and ignited in the muffle at a bright red heat, cooled and weighed.

The final weighings for the soil after reaching equilibrium in the desiccators are probably accurate to two or three milligrams, and the results are therefore reliable to about 0·02 per cent. The loss on ignition, however, is far less accurate, and there is some uncertainty in the end point even after prolonged ignition at bright red heat. Increasing the period by successive three-hour periods up to 12 hours gave, in most cases, increasing loss on ignition, but with certain soils there was sometimes an increase in weight when the time was lengthened, presumably on account of the oxidation of some residual constituent of the soil. On account of these fluctuations the accuracy of the final figures cannot be higher than about 0·2 per cent.

Sticky point (*S*). Although with practice the recognition of this point becomes an easy matter except for a few soils, the determination requires a certain amount of care if the results of different observers are to be comparable. Tests of this point are discussed separately below in Section 5 (*d*). A large number of experiments were first carried out with a small model mixing machine of the type used for dough and cordite, in which two horizontal shafts furnished with paddles and placed at the base of the machine, revolve inwards at different speeds. This machine effects a very thorough mixing of the soil and added water, but was unsuitable for our purpose because of the quantity of soil required (about 100 gm.) and the inconvenience caused by the dismantling and cleaning of the apparatus between the determinations for each soil. After several methods had been tried the following was adopted as standard: about 10 gm. of soil were spread in a thin layer on a glass plate and distilled water was added from a fine jet until the soil was definitely wet and sticky. The mass was then worked into a paste with a knife spatula. The wooden handled palette knife type with a flexible steel blade about 13 cm. long and 2¼ cm. broad was found very suitable for this purpose. The mass was then scraped from the plate and kneaded by hand until the soil just reached the stage at which it no longer stuck to the hands or the knife. At this stage it was possible to cut cleanly through the plastic mass with the knife. As already mentioned, this point could with a little practice be readily identified[1].

[1] In the earlier trials with the mixing machine the attainment of this condition was signalised by a perceptible cleaning-up of the metal base and sides of the apparatus, and it was because this observation was less likely to be influenced by personal judgment than the behaviour of the soil in the hands of the experimenter that the machine was tried in the first instance.

A sample of the kneaded soil, after weighing, was dried in the steam oven to determine the moisture content. At least two determinations were made for each soil, and they did not generally differ from each other by more than 1 per cent.

Determination of derived quantities from volume shrinkage experiments. The volume shrinkage of the soil was determined by the method described by Haines (11 *c*). From these data it is possible to calculate the pore space (P) of the oven-dried block, and the apparent and true specific gravities (σ, ρ) of the block (either before or after oven drying). An important characteristic of the shrinkage curve, depending upon the type of the soil, is defined by the moisture content (m) at which the first reading is taken.

Peroxide treated soils. With the exception of the air-dry moisture content, and the mechanical analysis (in which the peroxide and acid treatment were naturally used), the above observations were repeated on the soils after treatment with peroxide. The treatment followed that laid down in the British method of mechanical analysis (2 *a*), except that no acid was used. The soils were washed, dried at room temperature, and the dried cake was disintegrated with a wooden pestle.

5. Discussion of Experimental Results.

The data obtained are shown in Table II. As a preliminary, scatter diagrams were drawn to obtain some idea of the association between possible pairs of the experimental quantities, and the rough conclusions from these diagrams showed which associations were worth closer examination. It will be convenient to discuss firstly a number of smaller points before entering on the main examination of the data:

The moisture content (m) at the highest reading of the shrinkage curve is not a very sharply defined point but it is obviously closely related to the sticky point of the soil, and gives a high correlation with that quantity. Hence the length of the shrinkage curve can most usefully be defined by extrapolation to the latter value. Similarly the values for the air-dry moisture content (A) are closely related to the equilibrium moisture content at 50 per cent. relative humidity (R). The quantities (A) and (m) therefore need not be further considered.

The pore space as measured by the shrinkage experiment is not that of the soil in its normal state, but of a well-kneaded block. A measurement of pore space and the related quantities of real and apparent specific gravity in conditions similar to the field state was developed by one of us in an earlier paper (21), working with a series of successive depth

Table II.

Soil No.	Untreated samples										Peroxide treated samples					
	Shrinkage data				Moisture data						Shrinkage data			Moisture data		
	P	σ	ρ	m	A	R	S	C	I	$CaCO_3$	P	σ	ρ	R	S	I
1	26·5	1·83	2·49	21·4	1·99	1·81	34·3	15·2	7·29	0·7	20·6	2·06	2·59	1·62	19·8	4·09
2	35·0	1·54	2·36	43·3	3·55	3·05	56·7	20·7	13·76	0	21·3	1·97	2·50	1·14	30·0	8·98
3	27·6	1·76	2·44	36·5	3·51	3·27	46·0	23·9	11·68	tr.	26·7	1·85	2·52	2·38	29·5	6·53
4	26·7	1·80	2·46	17·7	1·15	1·10	27·3	7·2	5·12	tr.	21·7	1·87	2·38	0·96	22·2	3·04
5	22·7	1·95	2·60	14·3	1·46	1·30	19·7	7·4	3·60	0	18·6	1·95	2·44	0·98	17·2	2·14
6	24·8	1·90	2·53	17·4	1·37	1·29	22·3	8·3	4·45	0·021	17·6	2·00	2·42	1·01	16·6	2·18
7	23·5	1·98	2·59	27·2	3·15	2·93	26·8	21·7	5·27	0	22·1	2·00	2·57	3·17	27·0	4·67
8	23·3	2·00	2·60	31·0	3·52	3·13	30·1	27·2	6·75	0·180	22·3	2·02	2 60	3·46	29·4	5·08
9	27·3	1·88	2·58	30·2	5·12	2·59	28·8	21·8	9·13	1·8	22·6	1·98	2·56	2·87	27·4	6·14
10	28·2	1·85	2·57	26·2	2·29	2·09	29·3	13·9	6·25	0	21·6	1·98	2·52	1·88	21·2	3·73
11	31·0	1·71	2·48	21·9	1·55	1·45	27·4	8·4	4·75	0·02	23·8	1·84	2·41	0·94	22·0	2·27
12	37·2	1·58	2·52	30·5	3·39	3·28	44·7	1·4	9·04	0·303	26·5	1·84	2·50	2·13	27·9	5·16
13	34·3	1·64	2·49	26·4	2·48	2·41	43·1	1·4	9·23	0	24·7	1·79	2·37	1·91	24·8	4·15
14	35·5	1·62	2·52	24·5	3·56	3·29	36·9	1·9	8·82	tr.	25·8	1·73	2·38	2·74	33·8	7·47
15	24·8	1·91	2·54	13·5	1·19	1·06	22·2	0·3	3·60	tr.	19·8	1·93	2·40	0·95	20·1	2·07
16	23·3	1·95	2·61	38·8	6·12	5 26	35·0	52·0	13·09	10·9	21·0	1·96	2·48	5·29	37·2	14·30
17	23·9	1·94	2·55	40·4	5·80	4·99	38·8	45·0	11·46	1·2	21·5	1·98	2·53	5·39	33·7	6·18
18	16·5	2·11	2·53	38·3	9·37	8·82	39·1	47·6	8·13	2·13	16·2	2·14	2·56	8·57	40·0	8·65
19	17·2	2·11	2·55	42·8	7·83	7·17	33·7	40·8	9·42	3·81	15·4	2·14	2·53	7·68	35·7	7·64
20	34·4	1 63	2·48	43·4	2·89	2·41	45·4	19·8	9·85	tr.	25·2	1·88	2·51	1·76	28·3	4·32
21	37·2	1·53	2·43	35·9	0·53	0·48	40·6	44·2	12·34	0	38·2	1·52	2·46	0·60	43·5	12·42
22	25·9	1·77	2·39	20·2	1·88	1·50	29 8	6·6	7·73	0·05	22·0	1·95	2·50	1·35	20·9	3·42
23	21·4	1·93	2·46	18·7	1·49	1·15	21·4	8·7	4·27	0	19·5	2·02	2·52	1·44	19·5	2·35
24	23·7	1·88	2·46	31·0	4·06	3·54	37·2	22·9	7·32	0·06	17·2	2·01	2·52	3·29	27·4	4·84
25	21·3	2·00	2·74	34·7	5·16	4·28	37·0	30·9	6·25	0	19·0	2·02	2·49	4·53	32·0	4·94
26	21·0	1·96	2·49	27·3	3·53	2·99	33·1	21·7	11·46	11·62	19·2	2·04	2·53	3·33	30·3	11·00
27	22·5	2·01	2·60	28·5	3·46	2·87	30·8	23·0	14·71	22·80	18·6	2·04	2·50	3·26	29·4	14·27
28	25·0	1·88	2·51	19·7	2·14	1·87	26·8	10·8	4·92	0	22·2	1·93	2·48	1·73	23·1	2·59
29	23·4	1·91	2·50	25·2	3·20	2·48	30·8	17·1	5·12	0	22·5	1·96	2·53	2·47	27·8	3·09
30	28·1	1·60	2·23	23·5	2·21	1·89	29·9	12·4	5·42	0·13	22·7	1·92	2·48	2·00	23·7	2·96
31	26·4	1·63	2·21	22·8	2·10	1·83	27·4	15·6	4·30	0	24·2	1·91	2·52	2·11	24·3	2·64
32	26·5	1·64	2·23	21·3	1·64	1·50	26·9	7·2	4·52	0·12	21·0	1·93	2·44	1·11	18·8	2·11
33	22·5	2·10	2·58	17·9	1·29	1·10	22·7	8·8	2·98	0·04	22·4	1·96	2·53	1·25	20·7	2·64
34	26·2	1·86	2·53	20·8	2 20	2·05	31·9	10·1	5·11	0·26	22·1	1·93	2·48	1·97	21·9	2·66
35	25·4	1·93	2·59	24·0	2·36	1·94	28 8	12·8	4·52	0·10	22·5	1·94	2 50	2·47	25·1	2·95
36	21·9	1·42	1·82	58·3	6·46	5·46	77·6	24·7	20·59	0·04	25·6	1·72	2·31	3·67	46·6	10·95
37	25·5	1·83	2·46	46·6	5·81	4·85	50·7	40 5	8·80	0	25·5	1·91	2·57	4·44	33·6	6·24
38	21·0	1·98	2·51	34·4	5·61	4·67	39·7	31·3	8·33	0·42	19·2	2·01	2·49	4·45	29·3	6·23
39	32·5	1·73	2·57	38·0	6·24	5·10	40·1	36·3	6·29	0·11	20·0	2·02	2·52	5·14	29·2	5·62

samples of one soil, that were gently packed into small vessels perforated at the bottom, and placed in water. In these preliminary measurements the percentage of clay appeared to be inversely related to the apparent specific gravity and directly related to the pore space. Marchand (22), using the same method, did not confirm the former result with a series of Transvaal soils, but he did obtain a high correlation between clay and pore space.

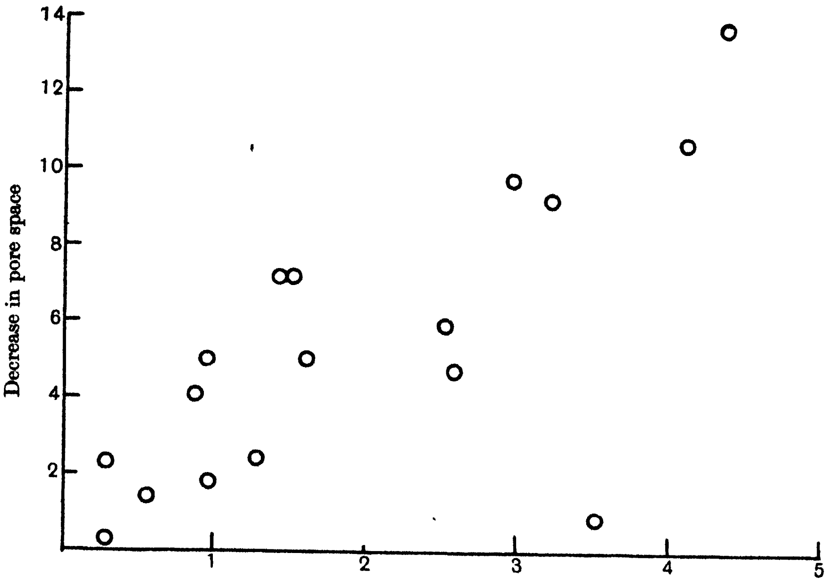


Fig. 1. Relation between organic carbon content and decrease in pore space after peroxide treatment.

In the present work there is no such relation between clay content and pore space in the dried plastic block, either for the original or the peroxide samples. It is evident that the thorough kneading tends to break down any compound particle structure and to encourage the individual grain to slip into closer packing. The bulk of the values for pore space fall around the average of roughly 26 per cent., although the clay and the organic matter contents vary widely. It is significant that the pore space of the peroxide treated soils is lower than that of the original samples in every case except two, and one of these (kaolin) is well within experimental error. This decrease may be attributed in a general way to the removal of the humified organic matter, permitting the individual mineral particles to slip into even closer packing than

before under the influence of the thorough kneading. The average reduction of pore space is 4–5 per cent. The reduction for the individual soil has been compared with the difference in the ignition values for the original and peroxide treated samples, which is a measure of the amount of humus removed by peroxide, but the correlation is hardly significant; the values for at least 10 of the soils fall widely away from the mean curve connecting the two variables. The figures for the organic carbon content of a certain number of the soils are available, and these show a close correlation with the decrease in pore space (Fig. 1), but the possibility that the complete series would show no better correlation than that of the ignition loss cannot be ignored. In any case the behaviour of the highly organic soils such as No. 36 (St Osyth Marsh top soil) requires further investigation: the pore space is increased from 21·9 to 25·6 per cent. after the action of peroxide.

(a) *General examination of data.*

The results of the complete examination of the associations between the different quantities can be expressed as correlation coefficients. From the scatter diagrams it appeared that the most important quantities were the percentage of clay (C), the moisture content at 50 per cent. relative humidity (R), the loss on ignition (I) and the sticky point (S).

Taking these in pairs, six correlations are possible, whose values are shown both for original and peroxide treated samples in Table III.

Table III. *Correlation coefficients between pairs of quantities.*

	A. Original soil				B. Peroxide treated soil		
	I	R	S		I	R	S
C	·364	·719	·317	C	·662	·760	·675
I	—	·388	·865	I	—	·386	·879
R	—	—	·503	R	—	—	·584

All these coefficients are definitely significant[1]; the lowest ($r_{CS} = 0{\cdot}317$) has a probability of more than 50 to 1. The table expresses the fact that in general the heavy clay soils have the highest ignition losses, moisture contents, and sticky points. It is significant that while four of the relationships are not appreciably altered by treatment of the soil with peroxide, the remaining two, connecting the clay content (C) with loss on ignition (I) and sticky point (S), are definitely increased. A closer

[1] The method followed is given in *Statistical Methods for Research Workers*, R. A. Fisher. (Oliver and Boyd, Edin. 15s.)

relation between C and I would certainly be expected, as with the removal of humified organic matter from the soil by peroxide the ignition loss will fall mainly on the clay fraction. The increased correlation between C and S indicates that the sticky point value is controlled both by the organic matter and some property related to the clay content. This point is returned to in more detail below (Section 5 (*c*)).

The highest correlations are between C and R, and between S and I; this is especially the case with the original soils. Taking partial correlation coefficients the association can be found between R and C when I is eliminated and between S and I when C is eliminated. The results are:

$$r_{SI.C} = 0{\cdot}843,$$
$$r_{RC.I} = 0{\cdot}673.$$

On the other hand the association between R and I when C is eliminated and between S and C when I is eliminated are practically negligible:

$$r_{RI.C} = 0{\cdot}194,$$
$$r_{SC.I} = 0{\cdot}155.$$

These four results lead to the important conclusion that the value of the sticky point is largely controlled by the material in the soil that is driven off by ignition, while the moisture content in the soil at half saturation vapour pressure (a value that is close to the "air"-dry moisture content) is controlled much more by the clay content as determined in a mechanical analysis.

Further confirmation of this distinction is afforded by the negligible correlations between I and R when S is eliminated and between S and C when R is eliminated:

$$r_{RI.S} = 0{\cdot}095,$$
$$r_{SC.R} = 0{\cdot}015.$$

The association of the water contents represented by R and S mainly with the clay and ignitable material respectively, points to a difference of degree if not of kind in the manner in which the water is held in the two cases. In conformity with both direct and indirect measurements of vapour pressure of moist soils (13 *a*, 13 *c*), the moisture represented by R may be regarded as held in the minute interstices and capillaries between the clay particles, while the moisture content S is held by the colloidal material which includes the organic colloids of the humic material and the inorganic colloids of the clay fraction. It should be unnecessary to point out that there is no sharp line of separation between the two water contents, as quite apart from other considerations, this

would imply that only the two quantities—clay and loss on ignition—were influencing the results. As it happens, the correlation between S and R is still just significant when both C and I are eliminated:

$$r_{SR.IC} = 0 \cdot 349.$$

However, the value of S obviously includes that part of the water held in the clay capillaries; if instead of S and R we obtain the correlation coefficient between $(S - R)$ and R, with I and C eliminated as before, the value falls below the level of significance:

$$r_{(S-R)R.IC} = 0 \cdot 140.$$

The high correlations between C and R, and I and S, therefore indicate a close causal association between the units of each pair of quantities.

The above conclusions are generally borne out by the partial correlations for the peroxide treated samples. These are given in Table IV, in which the values for the original soils are repeated for comparison.

Table IV. *Partial correlation coefficients.*

	Original soils	Peroxide treated soils
$r_{SI.C}$	·843	·782
$r_{CR.I}$	·673	·729
$r_{CS.I}$	·155	·260
$r_{IR.C}$	·194	·303

Two other points of interest emerge from the comparison. In the original soils there is no apparent connection between I and R when C is eliminated, while in the peroxide treated sample the correlation is just significant (0·303). A possible explanation lies in the fact that in each case the ignition loss includes about the same amount of "constitutional water" from the clay, which in the case of the peroxide treated samples forms the main contribution to the total ignition loss. It is reasonable to suppose that the "constitutional water" is related to the colloidal properties of the clay and therefore to its minute capillary or reticulate structure, in which the equilibrium moisture content denoted by R is retained. Hence a correlation between I and R would be expected when the so-called constitutional water forms an appreciable fraction of the total ignition loss.

The second point to be noted is that the high correlation between C and S for the peroxide treated soils (Table III B) is reduced below the level of significance when the partial correlation coefficient between C and S eliminating I is obtained.

(*b*) *Relation between organic matter and single value determinations.*

The contribution of the organic matter in the soil to the various single values can now be discussed in more detail. In the first place the

relation between the difference in the ignition losses for the original and peroxide treated soils $(I_o - I_p)$ and the actual organic matter content of the soil must be considered. As already mentioned a certain number of determinations of total carbon by the wet combustion method are available. The results, corrected for carbonate carbon, are shown in Table V, together with the total organic matter calculated on the conventional basis by multiplying the corrected carbon figure by 100/55.

Table V. *Relation between carbon content and ignition losses.*

Soil	Difference in loss on ignition $(I_o - I_p)$	Total carbon content, % on air-dry soil	Carbon content excluding carbonate carbon	Total organic matter (carbon × 100/55)
1	3·2	2·59	2·51	4·56
2	4·78	4·37	4·37	7·95
3	5·15	3·53	3·53	6·41
4	2·08	1·61	1·61	2·92
5	1·46	0·88	0·88	1·60
6	2·27	1·43	1·43	2·60
7	0·60	0·56	0·56	1·02
9	2·99	2·81	2·59	4·71
11	2·48	1·51	1·51	2·75
12	3·88	4·14	4·10	7·45
14	1·35	2·95	2·95	5·36
15	1·53	0·95	0·95	1·73
16	−1·21	2·56	0·28	0·51
17	5·28	1·42	1·28	2·33
18	−0·52	0·54	0·29	0·53
19	1·78	1·41	0·96	1·75
20	5·53	3·20	3·20	5·81
36	9·74	8·64	8·64	15·70

It is evident, from Table V, that the difference in ignition values before and after peroxide treatment is in general less than the total organic matter, if the values for the latter can be assumed as approximately correct. The relation between total organic matter and $(I_o - I_p)$ is shown in Fig. 2, which suggests that about 75 per cent. of the total organic matter is represented by $(I_o - I_p)$, or, in other words, is removed by peroxide treatment of the soils. The value agrees with estimates of other workers and will be adopted in the present paper. As it is not possible to give organic carbon values for all the soils it is desirable to point out that the fairly close relationship shown in Fig. 2 may not hold for the whole series for the reason already mentioned at the beginning of this section (p. 748).

(c) *Physical significance of the sticky point value.*

As the sticky point (S) is largely controlled by the ignitable material there should be a close correlation between the drop in its value as a result of peroxide treatment $(S_o - S_p)$ and the values of $(I_o - I_p)$. This

is so; the correlation coefficient between the two variables is 0·815. The sticky point is closely associated with the organic matter removed by peroxide and the ability to form an estimate of the actual amount so removed enables us to examine the relative contribution to the sticky point value of other factors besides organic matter. If we take the peroxide treated series we find, as already shown in Table III B, that the clay content C, and the sticky point S_p, are connected. The relationship is shown graphically in Fig. 3. Except for the four Craibstone soils

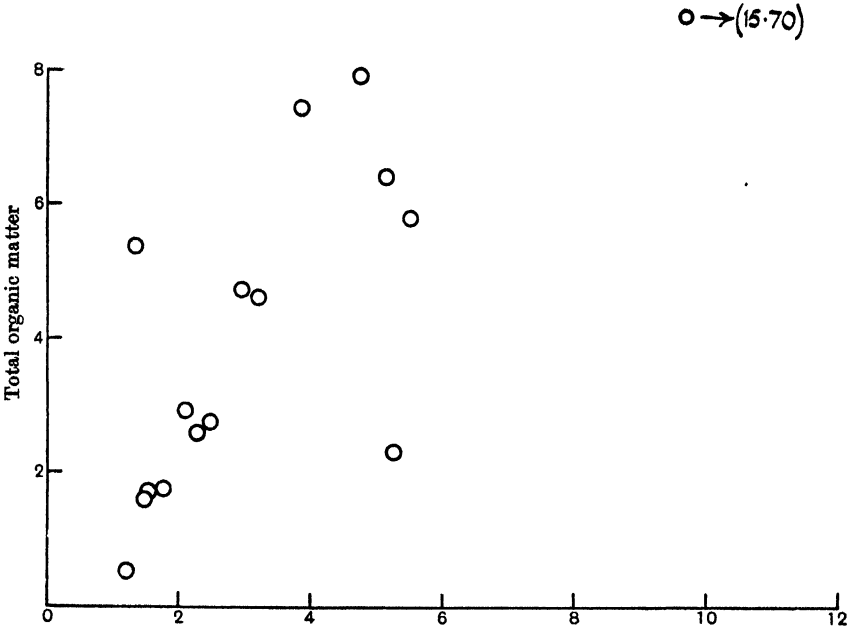


Fig. 2. Relation between total organic matter and difference in ignition loss of original and peroxide treated soils.

(Nos. 12, 13, 14, 15) and the highly organic marsh top soil (No. 36), whose sticky points are higher than the clay content would lead one to expect, the connection between the two variables is quite close, and can be represented quite fairly as linear. The line cuts the axis of S_p at about 16 per cent. moisture content.

This value represents the moisture content not associated with colloidal material, but present in the interstices of the plastic soil, *i.e.* the moisture content that would be held by a mass of sand worked up with water until its cohesion was about to disappear. The value of

16 per cent. is very close to 14·6 per cent. which is the calculated moisture content of an ideal soil in closest packing whose pore space is filled with water (23). The pore space of the ideal soil in closest packing is 26 per cent. and we have already seen that the average pore space for the original

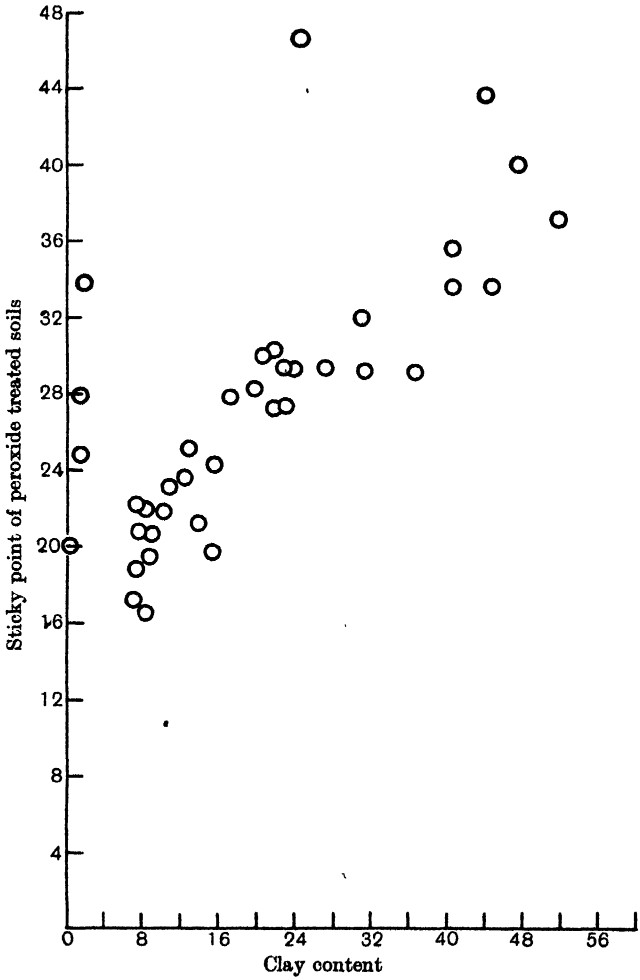


Fig. 3. Relation between clay content and sticky point of peroxide treated soils.

and peroxide treated samples is about 26 and 22 per cent. respectively. The process of kneading the soil in a sticky point determination produces a kind of statistical approximation to the condition in the ideal soil as far as the pore space is concerned, and hence we may with confidence identify the above mentioned moisture content of 16 per cent. as that

which occupies the pore space and is unassociated with colloidal material. This result is of interest in its bearing on Hardy's earlier work on West Indian soils (12). He developed the equation

$$\text{M.H.C.} = 23{\cdot}5 + S,$$

where
$$\text{M.H.C.} = \text{the moisture holding capacity},$$
$$23{\cdot}5 = \text{the film water},$$
$$S = \text{total colloidally imbibed water},$$

which is identified with the sticky point determination on the assumption that, at the sticky point, the swollen colloidal material occupies all the space between the mineral grains. In a later paper (24) he recognised that the moisture content of the sticky point is not all associated with the colloidal material. On the basis of ideal soil calculations already described (23) the value of one-fifth, or 20 per cent. by weight, is taken as the intersticial moisture content for a coherent sand. The experimental values of S are therefore reduced by a figure equal to one-fifth of the percentage of sand present in the soil and the value (S – % sand/5) taken as a measure of the water held by the colloidal material; Hardy suggests that this value is an index of soil texture and of use in soil survey work. Wilsdon (25) gave reasons for assuming that the ratio of the colloidally held water to the hydroscopic coefficient measured the vesicular coefficient of the soil colloids. Hardy's original and later postulates give respectively S/H and $[S - (\%\ \text{sand})/5]/H$ for this value, while the results given in the present paper lead to $(S - 16)/H$. In Table VI A and B these three ratios are compared for two series of experimental values given by Hardy.

The values for the modified ratios are naturally lower than those for S/H, since in each case the numerator of the fraction is reduced. Their values are also much steadier than those of S/H. Thus in Table VI A, values of S/H are higher for siliceous soils (top of table) than for laterites (lower half of table), as pointed out by Hardy, but this possible distinction is not borne out by the values of $(S - 16)/H$, which with three exceptions are singularly uniform. Similar results are shown in Table VI B.

Taking the whole data the value of $(S - 16)/H$ lies, with rare exceptions, between 2 and 4. There are obvious limitations to the significance of this result, apart from the indefinite nature of the hygroscopic coefficient. Nevertheless, it is suggestive, and worthy of further attention. A variation in the numerical value of the vesicular coefficient would be expected in view of the known differences in composition of colloidal material from one soil to another. At the same time the variation in

S/H seems larger than would be anticipated having regard to the smaller range of variation in other physical and physico-chemical properties over a wider range of soil types than those examined by Hardy, and hence the range of variations given by $(S - 16)/H$ appears more probable.

Table VI. *Comparison of values for vesicular coefficient.*

A. Hardy's data (12)

H	S	S/H	$(S-16)/H$
2·0	17·7	8·8	0·85
4·4	25·2	5·7	2·1
5·1	26·4	5·1	2·0
6·8	33·3	4·9	2·5
7·1	35·4	4·9	2·7
8·5	37·2	4·4	2·5
7·2	33·7	4·7	2·5
8·1	37·5	4·6	2·7
11·5	45·1	3·9	2·5
11·9	42·0	3·5	2·2
12·3	45·6	3·7	2·4
12·7	49·1	3·9	2·6
13·4	44·1	3·3	2·1
13·5	49·8	3·6	2·5
14·1	46·9	3·3	2·2
15·5	54·5	3·5	2·5
17·8	59·3	3·3	2·4
16·6	57·2	3·4	2·6
20·6	48·8	2·4	1·3
16·4	61·0	3·7	2·7
18·7	209·6	11·2	10·3

B. Hardy's data (24)

H	S	S/H	$(S-16)/H$	$\frac{S-(\%\text{ sand})/5}{H}$
3·6	28·1	7·8	3·4	4·8
9·0	47·8	5·3	3·5	4·8
4·7	35·3	7·5	4·1	5·9
7·3	42·4	5·8	3·8	5·2
9·6	44·7	4·7	3·0	4·4
10·3	46·5	4·5	3·0	4·2
11·0	53·8	4·9	3·4	4·6
12·7	51·5	4·1	2·8	3·8
4·0	25·0	6·2	2·3	3·2
3·6?	30·8	8·6	4·1	5·6
3·8	28·2	7·4	3·2	4·7
7·6	42·1	5·5	3·4	4·3
2·7	26·0	9·6	3·7	4·7
4·0	28·0	7·0	3·0	4·8
5·6	42·9	7·6	4·8	5·7
3·9	28·9	7·4	3·3	5·6
11·3	45·7	4·0	2·6	3·8
12·2	49·2	4·0	2·7	3·9
8·8	46·1	5·2	3·4	4·8
8·0	40·9	5·1	3·2	4·5
3·3	26·9	8·1	3·3	5·0
11·6	49·6	4·3	2·9	4·0
10·2	41·8	4·1	2·5	3·5
8·9	40·1	4·5	2·7	4·0

If we assume that the value of the sticky point determination is the additive effect of (1) the 16 per cent. of water held in the interstices, (2) the water held by organic colloidal material, and (3) water held by inorganic colloidal material associated mainly with the clay fraction, it is possible to obtain a rough estimate of the relative contribution of items (2) and (3). The colloidal organic material is taken as that removed by peroxide treatment as the remainder is structural organic matter and probably without much direct effect on the sticky point; its value is therefore $(I_o - I_p)$. There is no obvious measure of the inorganic colloidal material; it might be regarded as proportional to the total amount of clay, to the clay surface, or to the loss on ignition of the mineral part of the soil. The last value has been adopted, and taken as the ignition loss of the peroxide treated soil less the organic matter still present. On the assumption that $(I_o - I_p)$ represents three-fourths of the total organic matter, the amount still present after peroxide treatment is evidently $\frac{1}{3}(I_o - I_p)$.

The sticky points of the original and peroxide treated soils are respectively:

$$S_o = 16 + \alpha (I_o - I_p) + \beta (I_p - \tfrac{1}{3} (I_o - I_p)),$$
$$S_p = 16 + \beta (I_p - \tfrac{1}{3} (I_o - I_p)),$$

where α and β represent the amounts of water associated with unit weight of organic and inorganic colloidal material respectively.

The mean value of β is obtained from the slope of the best straight line through the scatter diagram for the two variables in the second equation. Subtraction of the second equation from the first gives

$$(S_o - S_p) = \alpha (I_o - I_p),$$

from which α is similarly obtained. In this case the points are rather widely scattered and the value of α is approximate. The values of α and β are respectively 3·3 and 2·8 so that the equation for the sticky point becomes

$$S_o = 16 + 3{\cdot}3 (I_o - I_p) + 2{\cdot}7 (I_p - \tfrac{1}{3} (I_o - I_p)).$$

The experimental values for S_o and those calculated from this equation are given in Table VII.

Table VII. *Comparison of calculated and experimental values for sticky point of untreated soils.*

Soil	S calcd.	S exptl.	S exptl. − S calcd.	Soil	S calcd.	S exptl.	S exptl. − S calcd.
1	35·1	34·3	− 1·8	21	(49·3)	40·6	(− 8·7)
2	47·0	56·7	9·7	22	35·8	29·8	− 6·0
3	41·4	46·0	4·6	23	27·1	21·4	− 5·7
4	26·2	27·3	1·1	24	35·4	37·2	1·8
5	24·3	19·7	− 4·6	25	32·9	37·0	4 1
6	24·1	22·3	− 2·8	26	49·5	33·1	− 16·4
7	39 3	26·8	− 12·5	27	56·9	30·8	− 26·1
8	34·1	30·1	− 4·0	28	30·8	26·8	− 4·0
9	41·3	28·8	− 12·5	29	31·0	30·8	− 0·2
10	32·4	29·3	− 3·1	30	30·0	29·9	− 0 1
11	24·7	27·4	2·7	31	27·3	27·4	0·1
12	39·6	44·7	5·1	32	27·7	26·9	− 0·8
13	37·8	43·1	5·3	33	24·2	22·7	− 1·5
14	40·1	36·9	− 3·2	34	29·2	31·9	2·7
15	25·4	22·2	− 3·2	35	28·0	28·8	0·8
16	(51·8)	35·0	(− 16·8)	36	69·7	77·6	7·9
17	45·5	38·8	− 6·7	37	39·5	50·7	11·2
18	(38·0)	39·1	(1·1)	38	38·4	39·7	1·3
19	41·6	33·7	− 7·9	39	33·3	40·1	6·8
20	41·3	45·4	4·1				

The agreement between experimental and calculated values is not good, and in fact only a qualitative agreement would be expected in view of the variety of assumptions made, and the experimental error in measuring the sticky points and the ignition losses. No attempt has been made, at this stage of the work, to improve the agreement by

altering the values of α and β. Their values indicate that unit weight of organic colloid takes up $(4/3) \times 3{\cdot}3$, *i.e.* 4·4 times its own weight of water, while the corresponding figure for the inorganic colloid is 2·7. These results show, therefore, that organic colloids take up slightly over 60 per cent. more water than an equal weight of inorganic colloids, when the latter are estimated in the manner suggested above. If, however, the clay content, C, be taken as a measure of the inorganic colloids in the above equations, the coefficient is found to be 0·5, which is only one-ninth of the coefficient for the organic colloids: a value in accordance with our knowledge of the relative efficiencies of the clay fraction and organic matter as water retaining colloids.

Table VIII. *Comparison of sticky point determinations by two workers A and B.*

	Original samples			Peroxide treated samples		
Soil	Worker A	Worker B	$A-B$	Worker A	Worker B	$A-B$
1	34·3	25·5	8·8	19·8	21·7	-1·9
2	56·7	52·1	4·6	30·0	30·8	-0·8
3	46·0	35·8	10·2	29·5	28·6	0·9
4	27·3	24·6	2·7	22·2	22·9	-0·7
5	19·7	19·0	0·7	17·2	17·6	-0·4
6	22·3	22·3	0·0	16·6	14·9	1·7
7	26·8	25·4	1·4	27·0	26·5	0·5
8	30·1	26·3	3·8	29·4	26·4	3·0
9	28·8	28·0	0·8	27·4	26·3	1·1
10	29·3	25·7	3·6	21·2	21·7	-0·5
11	27·4	28·5	-1·1	22·0	21·2	0·8
12	44·7	41·5	3·2	27·9	22·3	5·6
13	43·1	40·2	2·9	24·8	22·1	2·7
14	36·9	36·9	0·0	33·8	28·9	4·9
15	22·2	21·5	0·7	20·1	17·8	2·3
16	35·0	40·0	-5·0	37·2	36·4	0·8
17	38·8	48·3	-9·5	33·7	32·7	1·0
18	39·1	38·7	0·4	40·0	38·9	1·1
19	33·7	42·0	-8·3	35·7	33·2	2·5
20	45·4	44·0	1·4	28·3	23·3	5·0
21	40·6	35·6	5·0	43·5	33·5	10·0
22	29·8	31·4	-1·6	20·9	17·8	3·1
23	21·4	22·9	-1·5	19·5	17·8	1·7
24	37·2	31·0	6·2	27·4	23·9	3·5
25	37·0	28·8	8·2	32·0	26·6	5·4
26	33·1	27·2	5·9	30·3	23·8	6·5
27	30·8	26·1	4·7	29·4	23·3	6·1
28	26·8	25·9	0·9	23·1	21·5	1·6
29	—	—	—	27·8	23·3	4·5
30	—	—	—	23·7	22·1	1·6
31	—	—	—	24·3	22·2	2·1
32	—	—	—	18·8	18·2	0·6
33	—	—	—	20·7	19·0	1·7
34	—	—	—	21·9	20·8	1·1
35	—	—	—	25·1	21·9	3·2
36	—	—	—	46·6	39·4	7·2
37	—	—	—	33·6	36·3	2·7
38	—	—	—	29·3	27·4	1·9
39	—	—	—	29·2	30·9	1·7

(d) *Accuracy of the sticky point determination.*

As already mentioned in Section 4, the recognition of the sticky point appears to present no difficulty after a little experience of the method has been gained. Nevertheless a certain amount of personal judgment is involved and if the determination is to be generally adopted, some idea of the variation due to the personal equation is desirable. The sticky point determinations on the whole of the peroxide treated samples, and on 28 of the original samples were therefore independently repeated by another worker. The results are shown in Table VIII.

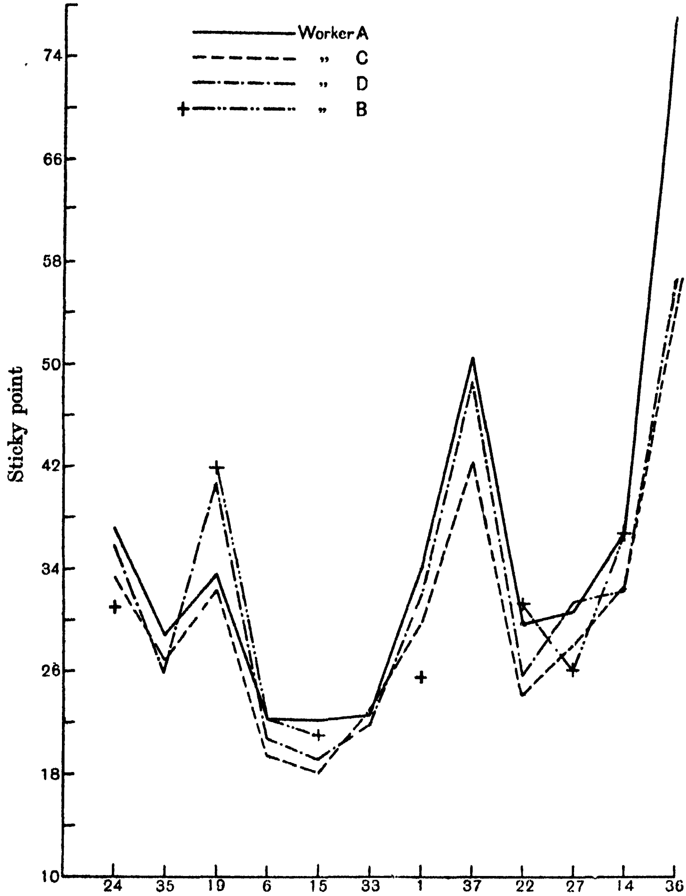


Fig. 4. Values obtained for sticky point of various soils by four workers.

It is evident that worker *A* generally obtains a higher value, and with

a few exceptions, that the differences are small. Taking the 67 pairs of parallel determinations the differences are distributed as follows:

$A \sim B$	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11
No. of soils	16	17	7	7	4	6	3	1	3	1	2

Thus in 33 cases (one-half of the total) the divergence is less than 2 per cent. moisture content, while in 51 cases (three-quarters of the total) it is less than 5 per cent. Some of the larger discrepancies are probably due to experimental error, *e.g.* peroxide treated kaolin (soil No. 21). Others are on heavy clays of an exceptional nature (Nos. 17 and 19). It is suggestive that in friction measurements with heavy clays Haines (26) obtained two maxima, corresponding to (*a*) a clean cut with a knife through the plastic mass, and (*b*) a state of incipient "flooding," in which the soil is just beginning to stick to external objects; it is possible that some similar effect explains the larger discrepancies here considered.

A further examination of the variation due to individual judgment was made with the help of two further workers, *C* and *D*. Twelve representative soils of the series were selected, and these two workers repeated the sticky point determinations. The experiment was made some considerable time after the work discussed in this paper had been concluded, and the workers *C* and *D* had only the written instructions for the sticky point determinations to guide them and had no previous experience with the method. Their results, and those of workers *A* and *B* for the same soils are set out diagrammatically in Fig. 4. It is evident from the figure that the trend of the results is the same in all cases, but, as with the more complete series of results for workers *A* and *B*, there are differences on individual soils. There is every reason to believe that the differences shown in Fig. 4 would be appreciably reduced after a little further experience[1].

6. Scope of Single Value Determinations.

The investigations discussed in this paper are not to be regarded as exhaustive, but rather as a preliminary study of the possibilities of simple single value determinations. The results are encouraging; the close association between the sticky point and colloidal material, and

[1] Later work, carried out by one of us (J. R. H. C.) on a number of South African soils will be discussed in a subsequent paper. It may be remarked here that replication of sticky-point measurements by two independent workers has been satisfactory—*e.g.* on 15 soils the average difference (neglecting signs) was 1·7 per cent., and there was no evidence that one worker obtained consistently higher values than the other.

between the moisture content at 50 per cent. relative humidity and the clay, strongly suggests that these two single value determinations are measuring soil properties that are reasonably distinct from one another. The determinations should therefore be correspondingly more useful, as coupled with a mechanical analysis, they enable soil to be specified from three different aspects. Again, repetition of the sticky point and ignition loss on peroxide treated soil gives additional information, offering the possibility—that needs further examination however—that the relative effects of organic and inorganic colloidal material can be distinguished.

There is urgent need for the adoption of additional methods of this nature. Under the impetus of the Russian school, soil classification and survey work have acquired a new and logical basis. The description of the soil profile however is still based very largely on a visual examination, and as long as this is so, a more detailed classification within any main soil type must remain qualitative, and dependent on the personal judgment of the observer. It appears that the single value measurements discussed in this paper are worth consideration as possible routine tests in connection with soil classification.

Apart from this, the methods have obvious application to the important physical and physico-chemical aspects of soil cultivation; this is now being followed up.

Further experience of the methods in the hands of different observers and on a wide range of soils is an essential preliminary to their general adoption. This has been arranged: the First Commission of the International Society of Soil Science decided at the Congress in Washington in June 1927 to organise an extensive series of co-operative experiments to this end, and the results will be reviewed at the next meeting of the Commission in June 1929.

7. Summary and Conclusions.

Numerous attempts have been made to devise an experimental method that, applied to a variety or a series of soils, enables them to be placed in an order closely reflecting their field behaviour or their most important physical characteristics. They are called "single-value" determinations as they endeavour to specify the soil by a single number, in distinction to the group of figures obtained, for example, from a mechanical analysis. A number of these methods are discussed in the present paper which contains an account of a detailed investigation on 39 soils of certain single value determinations.

The methods selected for study were chosen because (i) they required

only simple apparatus, and (ii) they appeared to be related to some distinct soil characteristic.

The list of measurements was as follows:

Percentage of clay.

Moisture content of soil in equilibrium with atmosphere of 50 per cent. relative humidity (the ordinary "air-dry moisture content" which was also determined, is close to this value).

Ignition loss of the dried soil.

Moisture content at the "sticky" point, which is defined as the point at which a thoroughly kneaded plastic mass of the soil is just about to stick to the fingers or to a knife.

The method of volume shrinkage developed by Haines was used to obtain the following additional quantities:

Moisture content of the saturated plastic block (this value closely approximates to the sticky point).

The pore space, true and apparent specific gravities of the oven-dried block.

The calcium carbonate present in each sample was determined, and on a number of the soils, total carbon content was also determined by the wet combustion method.

The most important feature of the present investigation was the repetition of the above measurements after the soils had been treated with hydrogen peroxide. Considerable experience of the effect of hydrogen peroxide on soil is now available owing to its inclusion in the Official British method of mechanical analysis, and our present knowledge indicates that it removes the humified and non-structural part of the organic matter without exercising more than a small solvent effect on the mineral portion of the soil. It has been assumed in the present investigation that the physical properties of the mineral portion are not appreciably altered by the peroxide. A comparison of the results for the original and peroxide treated soils thus gives an opportunity of comparing the relative contribution of the organic and the mineral portion of the soil to the single value measurements examined.

The main results obtained are set out below.

1. In spite of wide variations in clay and organic matter content the pore space of the kneaded blocks when oven dry fall closely around a mean figure of 26 per cent. This is reduced by 4–5 per cent. on the peroxide treated soils, and the effect is probably due to the ability of the grains to slip into closer packing under the influence of the thorough kneading, when the organic matter has been removed by the peroxide.

For the whole series of soils, however, the reduction in pore space is not related in a simple manner to the amount of organic matter removed. It is interesting to note that the pore space in the blocks of natural soils approximates to that of an ideal soil in closest packing (26 per cent.). Hence the process of kneading the soil in a sticky point determination produces a kind of statistical approximation to the ideal soil as far as total pore space is concerned.

2. Treatment with xide removes about 75 per cent. of the total organic matter present in the soil.

3. Correlation coefficients obtained for the various pairs of quantities examined express the general fact that the heavy clay soils have the highest ignition losses, moisture contents and sticky points.

4. An increased correlation between clay and sticky point for the peroxide treated soils suggests that the sticky point value is controlled both by the organic matter and some property related to the clay content.

5. When the associations are further examined by partial correlation coefficients, the sticky point is shown to be largely controlled by the colloidal organic and inorganic colloidal material, while the moisture content at 50 per cent. relative humidity is largely controlled by the actual clay content. There is independent evidence that this moisture is held in the minute interstices between the clay particles.

6. The sticky point approaches a lower limit of about 16 per cent. moisture content with very sandy soils containing little organic matter. This value is close to 14·6 per cent. which is the saturation moisture content of an ideal soil in closest packing, and it has already been shown that the pore space of this ideal soil and of the kneaded blocks of actual soil have approximately the same value. Hence the value of the sticky point moisture content is made up of (*a*) 16 per cent. of water held in the pore space, unassociated with colloidal material, and (*b*) water associated with inorganic and organic material. The division of the latter quantity into water associated with organic matter and inorganic clay colloids can be very approximately effected by assuming (i) that the difference between ignition losses of original and peroxide treated soil measures the effective organic matter, and (ii) that the ignition loss of the peroxide treated soil (less the organic matter still present) represents the clay colloid. On these assumptions it appears that the organic colloid takes up about 4·4 times its own weight of water, and the inorganic clay colloid 2·7 times its own weight. The approximate nature of the comparison must be emphasised, owing to the limitations in the assumptions

on which it is based. If the actual clay content be taken, instead of the ignition loss of the peroxide treated soil, as a measure of the inorganic colloid, the clay on a unit weight basis is only one-ninth as effective as the organic matter.

7. Measurements of the "vesicular coefficient" and "index of texture" made by Hardy are re-examined, allowance being made for the 16 per cent. of water not associated with colloidal material.

8. A comparison is made of the variation of sticky point determinations made by different workers and it is shown that satisfactory agreement can be secured after a little experience of the method.

9. The importance is stressed of introducing single value methods as an adjunct to the modern system of soil classification, and into soil physics.

ACKNOWLEDGMENTS.

Our thanks are due to Mr H. S. Rau for help in the experimental work, to Mr H. J. G. Hines for the determinations of organic carbon on a number of the soils, and to Mr W. E. de B. Diamond for supplying certain of the soil samples used in our investigation.

REFERENCES.

(1) Robinson, G. W. (1922). *J. Agric. Sci.* **12**, 287–91.

(2 *a*) Sub-committee of the A.E.A. (1926). *J. Agric. Sci.* **16**, 123–44. (*Rothamsted Memoirs*, **13**.)

(2 *b*) Sub-committee of the A.E.A. (1926). *Agric. Progress*, **3**, 106–9.

(2 *c*) Sub-committee of the A.E.A. (1928). *Agric. Progress*, **5**, 137–44.

(3 *a*) *Proc. First Int. Congress Soil Sci.* (*Washington*). (In the press.)

(3 *b*) Keen, B. A. (1928). *Soil Research*, **1**, 43–9.

(4) Odén, S. (1915). *Int. Mitt. Bodenk.* **5**, 257–311.

(5) Coutts, J. R. H. and Crowther, E. M. (1925). *Trans. Faraday Soc.* **21**, 374–80. (*Rothamsted Memoirs*, **13**.)

(6 *a*) Keen, B. A. (1920). *J. Agric. Sci.* **10**, 44–71. (*Rothamsted Memoirs*, **10**.)

(6 *b*) —— (1922). *Trans. Faraday Soc.* **17**, 228–43.

(6 *c*) —— (1926). *Physics in Industry* (Inst. of Physics), **4**, 29–63. (*Rothamsted Memoirs*, **13**.)

(7) Fisher, E. A. (1923). *J. Agric. Sci.* **13**, 121–43.

(8) Joffe, J. S. and McLean, H. C. (1925). *Soil Sci.* **20**, 169–74.

(9 *a*) Ashley, H. E. (1909). *U.S. Geol. Survey Bull.* 388.

(9 *b*) Gile, P. L., *et al.* (1924). *U.S. Dept. Agric. Bull.* 1193.

(9 *c*) Wilkinson, J. A. and Hoff, W. (1925). *J. Phys. Chem.* **29**, 808–15.

(10 *a*) Muntz, A. and Gaudechon, H. (1909). *Ann. Sci. Agron.* (3rd ser.), **4**, 393–443.

(10 *b*) Bouyoucos, G. J. (1925). *Soil Sci.* **19**, 152–61.

(11 *a*) Tempany, H. A. (1917). *J. Agric. Sci.* **8**, 312–30.

(11 *b*) Hardy, F. (1923). *J. Agric. Sci.* **13**, 243–64.

(11 *c*) Haines, W. B. (1923). *J. Agric. Sci.* **13**, 296–310. (*Rothamsted Memoirs*, **12**.)

(12) HARDY, F. (1923). *J. Agric. Sci.* **13**, 340–51.

(13 *a*) PURI, A. N., CROWTHER, E. M. and KEEN, B. A. (1925). *J. Agric. Sci.* **15**, 68–88. (*Rothamsted Memoirs*, **12**.)

(13 *b*) PURI, A. N. (1925). *J. Agric. Sci.* **15**, 272–83. (*Rothamsted Memoirs*, **12**.)

(13 *c*) CROWTHER, E. M. and PURI, A. N. (1924). *Proc. Roy. Soc.* A. **106**, 232–42. (*Rothamsted Memoirs*, **12**.)

(14) ALWAY, F. J. (1913). *Nebraska Expt. Sta. Res. Bull.* 3.

(15) SHULL, C. A. (1916). *Bot. Gaz.* **62**, 1–31.

(16) CAMERON, F. K. and GALLAGHER, F. E. (1908). *U.S. Bureau of Soils Bull.* 50.

(17) SHAW, C. F. (1927). *Soil Sci.* **23**, 303–17.

(18) KEEN, B. A., CROWTHER, E. M. and COUTTS, J. R. H. (1926). *J. Agric. Sci.* **16**, 105–22. (*Rothamsted Memoirs*, **13**.)

(19) HAINES, W. B. (1925 and 1927). *J. Agric. Sci.* **15**, 529–35; **17**, 264–90. (*Rothamsted Memoirs*, **13**.)

(20) FISHER, R. A. (1926 and 1928). *J. Agric. Sci.* **16**, 492–505. (*Rothamsted Memoirs*, **13**.) **18**, 406.

(21) KEEN, B. A. and RACZKOWSKI, H. (1921). *J. Agric. Sci.* **11**, 441–49. (*Rothamsted Memoirs*, **11**.)

(22) MARCHAND, B. DE C. (1926). *South African J. Sci.* **23**, 238–43.

(23) KEEN, B. A. (1924). *J. Agric. Sci.* **14**, 170–7. (*Rothamsted Memoirs*, **12**.)

(24) HARDY, F. (1928). *J. Agric. Sci.* **18**, 252–6.

(25) WILSDON, B. H. (1921). *Mem. Dept. Agric. India, Chem. Series*, **6**, 154–84.

(26) HAINES, W. B. (1925). *J. Agric. Sci.* **15**, 178–200. (*Rothamsted Memoirs*, **12**.)

(*Received July 28th*, 1928.)

DIGESTIBILITY TRIALS WITH POULTRY.

VI. ON THE INFLUENCE OF THE SIZE OF A RATION UPON ITS DIGESTIBILITY.

By E. T. HALNAN.

(Poultry Nutrition Section, Animal Nutrition Institute, School of Agriculture, Cambridge.)

THE application of scientific feeding standards to the computation of rations for animals involves the tacit assumption that the digestibility of the food nutrients is not substantially altered as the quantity fed is increased. This assumption, so far as coarse fodders are concerned, has been shown to be correct for ruminants by workers in this field of animal husbandry. In the case of rations consisting of mixtures of coarse fodders and concentrates, evidence has been brought forward which suggests that heavy feeding is associated with a depression of digestibility, the nutrients of a maintenance ration being more efficiently digested than those of a super-maintenance ration (1). Thus in unpublished experiments on steers by Armsby and Fries a depression of digestibility was shown to occur in the case of three steers fed on increasing amounts of a uniform mixture of two-thirds grain and one-third hay. The differences in digestibility shown between these three individuals on the same amount of food were, however, as large as the differences in digestibility shown between the varying amounts fed to the same individual. Thus, taking the organic matter as a basis of comparison, the digestibility varied from 68·8 per cent. to 74·9 per cent. in the same individual on different amounts of food, whereas it fluctuated from 68·8 per cent. to 75·1 per cent. among the different individuals when fed on the same amount of food. It can therefore be safely assumed, that even in the case of rations consisting of mixtures of concentrates and fodders, where a depression of digestibility appears to follow increase in size of ration, this apparent depression of digestibility is not sufficiently large to affect materially the results of computations based on the assumption that the digestibility of a ration does not alter with variations in the quantities fed. The fact that such a depression of digestibility, however insignificant, apparently occurs in ruminants, rendered it very desirable to ascertain the possibility of its occurrence in poultry, since the existence of a simpler alimentary tract of a relatively smaller capacity in birds was more likely to be associated

with a depression of digestibility due to increase of food intake. Moreover, in certain experiments carried out in this laboratory with fowls, the assumption had been made that increase of food intake was not followed by a depression of digestibility, and if this assumption were not true, the conclusions arrived at would be materially affected. Accordingly, a series of trials were instituted to test this point.

Description of trials.

The birds used in these trials (four White Leghorns) were housed in roomy wire cages so fitted as to facilitate quantitative collection of excreta, and were fed twice daily on a wet mash made by the addition of distilled water to a mixture of 9 parts by weight of Sussex ground oats and 1 part by weight of full cream milk powder. The excreta were removed once daily, and after thorough mixing to ensure even sampling, an aliquot portion of each bird's excreta was placed in a suitable glass container and kept in cold store at an approximate temperature of 0° C. At the conclusion of each collection period, the composite sample of each bird's excreta so obtained was analysed, the analytical procedure outlined in a previous communication being adopted (2). Each trial was divided into three feeding periods, 50 gm. per head per day of the dry food being fed in the first period, 100 gm. in the second period, and 150 gm. in the third period. Each collection period consisted of 12 days, except in the case of birds 3 and 4 in Period III, where it was found necessary, owing to failure of appetite, to limit the period of collection to 8 days. The data obtained were as follows:

Average composition of food fed.

Moisture	10·22 %	Ether ext.	7·50 %
Protein	13·06	Fibre	6·80
N-free ext.	58·92	Ash	3·50

Protocol of experimental and analytical data.

	Period of collection days	Dry excreta gm.	Total organic matter gm.	Total nitrogen gm.	Uric acid nitrogen gm.	Ammoniacal nitrogen gm.	Crude fat gm.	Crude fibre gm.	Ash gm.
	Period I (50 gm. food per bird per day)								
Bird 1	12	219·70	197·82	12·39	6·84	1·37	5·99	38·61	21·88
Bird 2	12	216·74	195·64	14·36	9·77	1·18	4·87	35 20	21·10
Bird 3	12	201·82	178·99	11·22	6·48	1·22	4·20	37·98	22·83
Bird 4	12	217·21	194·17	12·74	8·36	1·56	4·53	39·92	23·04
	Period II (100 gm. food per bird per day)								
Bird 1	12	423·59	384·73	19·70	10·23	2·26	8·46	80·62	38·86
Bird 2	12	446·65	406·35	21·71	12·17	2·31	7·22	86·60	40·30
Bird 3	12	420·34	378·56	21·76	13·40	2·82	8·54	81·73	41·78
Bird 4	12	393·60	355·80	17·91	10·81	2·12	7·08	74·27	37·80

Period III (150 gm. food per day per bird)

	Period of collection days	Dry excreta gm.	Total organic matter gm.	Total nitrogen gm.	Uric acid nitrogen gm.	Ammoniacal nitrogen gm.	Crude fat gm.	Crude fibre gm.	Ash gm.
Bird 1	12	656·34	598·66	32·00	15·20	3·78	15·63	120·13	57·68
Bird 2	12	642·66	586·44	30·80	14·51	3·12	11·17	113·70	56·22
Bird 3	8	389·95	352·14	20·26	12·81	2·21	7·39	76·04	37·81
Bird 4	8	451·64	408·84	16·97	9·60	2·34	8·61	88·74	42·80

Average composition of the dung in gm. actual weight (calculated).

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Period I					
Bird 1	167·37	19·06	5·44	38·61	104·26
Bird 2	154·86	11·56	4·14	35·20	103·96
Bird 3	150·43	15·38	3·69	37·98	93·38
Bird 4	157·20	8·75	3·87	39·92	104·66
Period II					
Bird 1	338·47	34·44	7·63	80·62	215·78
Bird 2	352·66	32·75	6·25	86·60	227·06
Bird 3	318·18	20·25	7·45	81·73	208·75
Bird 4	307·71	19·75	6·21	74·27	207·48
Period III					
Bird 1	528·54	65·56	14·37	120·13	328·48
Bird 2	521·37	67·75	10·00	113·70	329·92
Bird 3	296·26	19·50	6·39	76·04	194·33
Bird 4	364·50	21·06	7·81	88·74	246·89

Digestibility coefficients of S.G.O. and milk mixture.

Period I (50 gm. food per bird per day)

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Bird 1					
600 gm. food contain	517·68 gm.	78·36 gm.	45·00 gm.	40·80 gm.	353·52 gm.
Dung contains	167·37	19·06	5·44	38·61	104·26
Digested	350·31	59·30	39·56	2·19	249·26
Dig. coefficient	67·7 %	75·7 %	87·9 %	5·4 %	70·5 %
Bird 2					
600 gm. food contain	517·68 gm.	78·36 gm.	45·00 gm.	40·80 gm.	353·52 gm.
Dung contains	154·86	11·56	4·14	35·20	103·96
Digested	362·82	66·80	40·86	5·60	249·56
Dig. coefficient	70·1 %	85·3 %	90·8 %	13·7 %	70·6 %
Bird 3					
600 gm. food contain	517·68 gm.	78·36 gm.	45·00 gm.	40·80 gm.	353·52 gm.
Dung contains	150·43	15·38	3·69	37·98	93·38
Digested	367·25	62·98	41·31	2·82	260·14
Dig. coefficient	69·6 %	80·4 %	91·8 %	6·9 %	73·6 %
Bird 4					
600 gm. food contain	517·68 gm.	78·36 gm.	45·00 gm.	40·80 gm.	353·52 gm.
Dung contains	157·20	8·75	3·87	39·92	104·66
Digested	360·48	69·61	41·13	0·88	248·86
Dig. coefficient	69·6 %	88·8 %	91·4 %	2·2 %	70·7 %
Average dig. coefficient	**69·3 %**	**82·6 %**	**90·5 %**	**7·1 %**	**71·4 %**

Period II (100 gm. food per bird per day)

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Bird 1					
1200 gm. food contain	1035·36 gm.	156·72 gm.	90·00 gm.	81·60 gm.	707·04 gm.
Dung contains	338·47	34·44	7·63	80·62	215·78
Digested	696·89	122·28	82·37	0·98	491·26
Dig. coefficient	67·5 %	78·1 %	91·5 %	1·2 %	69·5 %
Bird 2					
1200 gm. food contain	1035·36 gm.	156·72 gm.	90·00 gm.	81·60 gm.	707·04 gm.
Dung contains	352·66	32·75	6·25	86·60	227·06
Digested	682·70	123·97	83·75	—	479·98
Dig. coefficient	66·1 %	79·1 %	93·1 %	—	67·9 %
Bird 3					
1200 gm. food contain	1035·36 gm.	156·72 gm.	90·00 gm.	81·60 gm.	707·04 gm.
Dung contains	318·18	20·25	7·45	81·73	208·75
Digested	717·18	136·47	82·55	—	498·29
Dig. coefficient	69·5 %	87·1 %	91·8 %	—	70·5 %
Bird 4					
1200 gm. food contain	1035·36 gm.	156·72 gm.	90·00 gm.	81·60 gm.	707·04 gm.
Dung contains	307·71	19·75	6·21	74·27	207·48
Digested	727·65	136·97	83·79	7·33	499·56
Dig. coefficient	69·2 %	87·4 %	93·1 %	9·0 %	70·7 %
Average dig. coefficient	**68·1** %	**82·9** %	**92·6** %	—	**69·7** %

Period III (150 gm. food per bird per day)

	Organic matter	Crude protein	Ether extract	Crude fibre	N-free extract
Bird 1					
1800 gm. food contain	1553·04 gm.	235·08 gm.	135·00 gm.	122·40 gm.	1060·56 gm.
Dung contains	528·54	65·56	14·37	120·13	328·48
Digested	1024·50	169·52	120·63	2·27	732·08
Dig. coefficient	66·0 %	72·1 %	89·3 %	1·9 %	69·0 %
Bird 2					
1800 gm. food contain	1553·04 gm.	235·08 gm.	135·00 gm.	122·40 gm.	1060·56 gm.
Dung contains	521·37	67·75	10·00	113·70	329·92
Digested	1031·67	167·33	125·00	8·70	730·64
Dig. coefficient	66·5 %	71·2 %	92·6 %	7·1 %	68·9 %
Bird 3					
1200 gm. food contain	1035·36 gm.	156·72 gm.	90·00 gm.	81·60 gm.	707·04 gm.
Dung contains	296·26	19·50	6·39	76·04	194·33
Digested	739·10	137·22	83·61	5·56	512·71
Dig. coefficient	71·6 %	87·6 %	92·9 %	6·8 %	72·5 %
Bird 4					
1200 gm. food contain	1035·36 gm.	156·72 gm.	90·00 gm.	81·60 gm.	707·04 gm.
Dung contains	364·50	21·06	7·81	88·74	246·89
Digested	670·86	135·66	82·19	—	460·15
Dig. coefficient	65·0 %	86·6 %	91·3 %	—	65·1 %
Average dig. coefficient	**67·3** %	**79·4** %	**91·5** %	—	**68·9** %

Quantitative effect of food on digestibility coefficients.

Quantity of food per bird per day gm.	Average digestibility coefficient Organic matter %	Crude protein %	Ether extract %	N-free extract %
50	**69·3**	**82·6**	**90·5**	**71·4**
100	**68·1**	**82·9**	**92·6**	**69·7**
150	**67·3**	**79·4**	**91·5**	**68·9**

Discussion and Summary.

Consideration of the figures obtained in the trials above reported would indicate that the effect of increasing the amount of food fed to poultry is to depress to a slight extent the coefficients of digestibility of the digestible nutrients. If the individual coefficients of digestibility for each nutrient are compared in each period, it will be noted that the indicated depression of digestibility is in all cases considerably less than the normal fluctuation within each group. Thus, in the case of the organic matter, the depression of digestibility amounts to 2 per cent., the normal fluctuation within the groups varying from 2·4 per cent. in Period I to 6·6 per cent. in Period III. In the case of the ether extract, there is an increase in the digestibility of 2·1 per cent., but here again the normal fluctuation within the groups varies from 3·9 per cent. in Period I to 1·6 per cent. in Period II. The same phenomenon is shown in the case of the N-free extract and the crude protein, the depression of digestibilities being 2·5 per cent. and 3·2 per cent. respectively, whereas the normal fluctuations vary from 2·8 per cent. in Period II to 7·4 per cent. in Period III in the case of the N-free extract and from 9·0 per cent. in Period II to 16·4 per cent. in Period III in the case of the crude protein. There is, therefore, a strong probability that the slight depressions in digestibility of the organic matter, the N-free extract and the crude protein, and the slight increase in digestibility of the ether extract shown in the above experiments are not significant and lie within the margin of experimental error, and it can be stated with a considerable degree of confidence that increasing the quantity of food to fowls does not alter the digestibility of the nutrients. In the experiments cited, the amounts of food consumed varied from a slightly sub-maintenance ration to a ration that approximated very closely to the limit of the birds' appetites.

Summary.

1. Four White Leghorn cockerels were fed with widely varying quantities of a Sussex ground oats and milk mixture without material alteration in the coefficients of digestibility of the digestible nutrients.

2. The amounts fed varied from a sub-maintenance ration of 50 gm. to a "limit of appetite" ration of 150 gm. A slight depression in the coefficients of digestibility of the organic matter, the crude protein and the N-free extract, and a slight increase in the coefficient of digestibility of the ether extract was obtained, but the differences shown are attri-

buted to normal fluctuations in digestibility due to individual variation and not to differences in the quantity of food given.

3. In feeding experiments carried out with fowls, in which variable amounts of food are fed, these experiments indicate that it may safely be assumed that the coefficients of digestibility of the food nutrients are not materially affected by the variations in the amounts of food fed.

REFERENCES.

(1) ARMSBY, H. P. *The Nutrition of Farm Animals*, p. 615.
(2) HALNAN, E. T. *J. Agric. Sci.* **16**, 451.

(*Received June* 11*th*, 1928.)

PRELIMINARY INVESTIGATION ON THE FECUNDITY OF PREMIUM STALLIONS.

By ARTHUR WALTON, B.Sc., Ph.D. and T. KEITH FAIR, B.A.
(*School of Agriculture, Cambridge.*)

A recent statistical survey of the records of premium stallions by Sanders (1) draws attention to the fact that the breeding efficiency of the horse is much below that of the other domesticated animals and that it has apparently declined within recent years. For example, between 1887 and 1889 the average number of mares served by Light Horse stallions and which produced foals was about 59 per cent. of the total mares served. Between 1904 and 1910 this figure had fallen to about 56 per cent. and at the present time is not much above 50 per cent. While this decline may in part be due to the record of infertile services being kept more strictly now than formerly, and perhaps also to the more rigorous conditions to which travelling stallions are subjected, the figures are sufficient to indicate that much loss is actually occasioned by low breeding efficiency and also that there might be considerable improvement on the present standard.

The fertility of a mating will naturally depend upon both partners; the stallion and the mare. It is generally recognised that the condition of the latter is of primary importance. There seems to be no doubt that a mare served on the ninth or tenth day after foaling has a much greater chance of being impregnated than if served at later heat periods, especially if suckling. With mares which have not recently been pregnant the chance of impregnation will also depend upon the time after the beginning of heat at which service takes place, the general opinion being that service on or after the third day is the most favourable time. Nutritional, seasonal and climatic conditions will also undoubtedly influence the chances of successful impregnation. These factors affecting the fertility of the mare are now being investigated experimentally and in detail at this Institute by Mr Hammond and Dr Sanders. The part which the stallion plays in determining fertility is not so well recognised and is not so amenable to direct experimentation. A very large number of mares would be required in order to test directly the fertility of a stallion under various conditions and at various times. Facilities for large-scale experimentation are not available and the cost would be almost prohibitive. Some information may be derived from statistical enquiries.

For example, Sanders has shown that the fertility of premium stallions varies very considerably and that high or low fertility may characterise a stallion, independently of the mares served. There is also a significant decline in fertility of the stallion with advancing age. Other factors, such as the number of mares served in a season, or the district variation, have less important influences. This statistical research is of undoubted value, especially in orientating further enquiry, but unfortunately gives little information on the direct causes of low fertility.

From theoretical considerations based upon experimentation (see Walton (2)) the fertility of a stallion will depend upon two main factors which together constitute what may be termed the *effective fecundity* of the stallion; first, the number of spermatozoa ejaculated at service and, secondly, the activity and viability of the individual spermatozoa. A stallion which ejaculates a large number of active and highly viable spermatozoa will presumably have on the average a higher fertility than one which ejaculates only a small number of sperms which are deficient in activity and viability. If this relationship could be established by actual examination of the semen it would provide further support for the theoretical concepts derived from experimentation and might give useful information on the causes of low fertility and the means of avoiding it. From a practical standpoint it would also enable the fertility of a stallion to be assessed early in the season and independently of the fertility of the mares served. At the present time the fertility of a stallion can only be gauged approximately by the number of mares which return to the horse after service. A strictly reliable measure is not available until the following year, when the foaling returns are collected.

Our scheme was therefore to examine the semen of a number of stallions and to see whether differences in the number, activity and viability of the spermatozoa would explain the actual differences in fertility which they exhibit. Through the intermediary of the Ministry of Agriculture we obtained permission from the War Office authorities to carry out the tests on the Light Horse premium stallions, whose service records are accurately kept and extend over a considerable number of consecutive years, thus enabling reliable returns of fertility to be made. Permission was also obtained from the owners of the stallions and of the mares used for the collection of the semen and to these gentlemen our grateful thanks are due. We are also greatly indebted to Captain Campbell, Horse Breeding Officer for the Eastern District, and to the District Remount Officers who were exceedingly helpful in making the necessary arrangements for the tests.

At our request the War Office authorities gave us a list of six stallions, three of which were expected to give high fertility returns and three of which were suspected of low fertility. We were not informed of the class to which each stallion belonged. In this way the tests were carried out as far as possible without influence of previous judgments.

Since the mares from which we were permitted to remove the semen were destined by the owners for breeding purposes it was desirable to employ only the simplest methods involving the very minimum of interference. The stallion was allowed to serve the mare as in usual practice. Marshall and Crosland (3) in their investigation into the low fertility of horses mention cases where the semen was extruded by the mare straining after service. Particular note was therefore taken to see that this did not occur previous to examination. Only in one case (Table I, Stallion *C*) was extrusion noted and this in a mare which was not used for the purpose of the test. Immediately after service the hand of the operator was inserted into the vagina of the mare, a little medicinal paraffin on the back of the hand and arm being used as a lubricant. The operation can be performed without the adoption of any stringent methods of control and in actual practice the mares gave no trouble. As a precaution against kicking, however, the service hobbles were retained or the fore-foot of the mare held up by an assistant.

If there had been a satisfactory service the semen could be felt lying in a pool near the cervix. By cupping the fingers the semen could be withdrawn from the vagina and was caught in a small "Pyrex" glass bowl held in readiness by an assistant. The volume of the sample withdrawn gave some indication of the quantity of semen ejaculated and observations were taken with regard to its cleanliness and other properties. There is considerable danger of contamination with urine owing to the mare micturating during the insertion or withdrawal of the hand of the operator. This contamination will seriously affect the value of the sample by reducing the density of the spermatozoa and possibly also affecting their activity and viability. In these circumstances it is advisable to obtain another sample.

A drop of the semen was examined microscopically immediately after withdrawal and observations made on the motility of the spermatozoa and other characteristics of the sample. Smear preparations were also made and fixed in osmic acid vapour and subsequently stained and examined after return to the laboratory. The bulk of the semen was transferred to stoppered test-tubes held in a metal frame and placed in a large vacuum flask filled with water. The flask and its contents were kept at a constant temperature of 10° C. by the addition from time to

Table I. *Report on the Fecundity of Premium Stallions.*

Stallion	General condition (sexual vigour, etc.)	Semen	Predicted fertility
F	Previous service morning before. Stallion keen and active and served mare without delay	Quantity: about 50 c.c. of clean, somewhat viscous semen Sperms: 90–95 % motile; fully active; normal appearance Viability: 5½ hr. about 10 % motile; not very active Density: 14,000,000 per c.c.	High
B	Previous service same morning. Stallion keen and active, at the same time exceptionally easily controlled	Quantity: about 50 c.c. of clean semen Sperms: 90–95 % motile fully active; normal appearance Viability: 6 hr. completely immotile Density: 11,700,000 per c.c.	High
D	Previous service a day or two before. Stallion fairly vigorous and keen. Service somewhat prolonged	First sample contaminated with urine, second sample clean Quantity: 20 c.c., rather fluid Sperms: 50 % motile; fairly active Viability: 3 hr. only 3 % motile Density: 60,780,000 per c.c.	High
A	Previous service day before. Stallion very vigorous and keen, somewhat intractable. Mare served on 9th day after difficult parturition, vagina constricted and penetration difficult. (The stallion was visited on three subsequent occasions but no mares proved available for the test)	Semen much contaminated with post-partum debris Quantity: about 20 c.c., including contamination from mare Sperms: fairly plentiful; active and normal appearance Viability: owing to contamination estimation impracticable Density: owing to contamination estimation impracticable	Test unsatisfactory but probably high
C	Previous service ½ hr. before with mare not available for manual examination, but small sample of semen extruded and subsequently examined. Test service: stallion keen and vigorous; service somewhat protracted	No semen obtained from vagina of test mare; few drops from vulva, and small quantity of semen available for examination from the non-test mare Quantity: very small Sperms: few sperms 20 % motile; some fairly active; many immature Viability: ½ hr. completely immotile Density: sample insufficient, probably very low	Low
G	Previous service 3 days before. Stallion in good condition and fairly keen. Served maiden mare with some difficulty. Service apparently normal but no semen obtained. One hour later served same mare with same result	No semen obtained	Low
E	Previous service same day. Served mare fairly vigorously, but stallion appeared somewhat exhausted. No semen obtained. ¼ hr. later horse again tried, but for some time failed to get erection. Finally an apparently satisfactory service was obtained, but only sufficient semen to make smears. (Stallion possibly out of condition or overworked)	Quantity: very small Sperms: 20 % motile; fairly active; normal appearance Viability: sample insufficient Density: sample insufficient	Low

time of small quantities of ice or ice-cold water, a stock of which was carried in a second vacuum flask. The temperature (10° C.) was selected as that at which the spermatozoa of the rabbit retain their fertilising capacity longest[1]. It was our original intention to measure the viability of the spermatozoa by estimating the percentage actively motile at various intervals after service. On the few occasions on which we obtained sufficient semen we found that the survival of the spermatozoa was extremely short and this fact, added to the difficulty of making an examination "en route" or at untoward hours of the day and night, prevented our obtaining results of really critical value. After return to the laboratory an estimate of the "density" or number of spermatozoa per cubic centimetre was made, using the technique described in a previous communication (Walton (2)). One of the stallions on the War Office list was travelling at some considerable distance from Cambridge and was not tested, but two less inaccessible horses were substituted. The results of the investigation of the seven stallions are shown in Table I.

As far as the tests go the most significant feature is that total or partial failure to ejaculate (Stallions *C*, *G*, *E*) is not an uncommon occurrence even when the service is apparently perfectly satisfactory. A high incidence of such services would sufficiently explain the low fertility of a stallion. It would, however, be unjustifiable to condemn a horse for frequent or periodic non-ejaculation on the basis of a single test and we categorise these stallions as having low fertility only with considerable reservation. With regard to other differences in the semen, density, viability, etc., our general conclusion is also that the methods of sampling are subject to too many variables to provide conclusive results on the basis of a single test. Undoubtedly it would have been much more satisfactory to carry out more than one test on each stallion, and it was our original intention to do so, but experience showed that arrangements for the test involved a considerable amount of time, and towards the close of the season, when fewer mares are available for service, many fruitless journeys, involving much expense and loss of time might have to be made (see Stallion *A*). It was decided therefore not to continue the tests this season.

In Table I the stallions have been placed in order of predicted fertility and the same noted in the last column. Whether this prediction is justifiable will only be seen when actual returns of percentage fertility are available in the spring of 1929, but owing to the inadequacy of the tests made we do not attach very much significance to the prediction.

[1] Experiments in progress.

The investigation has been of value in drawing attention to the possibility that non-ejaculation may be a prevalent cause of low fertility and useful information has been obtained on the technique of sampling and the difficulties involved.

With regard to future work, we are of opinion that before attempting further tests the technique of sampling should be worked out in greater detail and a large series of determinations made upon one stallion with a view to standardising the methods and obtaining some information on the variability of sampling. It is possible that facilities for this work will be available at Cambridge.

REFERENCES.

(1) SANDERS (1926). *J. Agric. Sci.* **16**, 466–91.

(2) WALTON (1927). *Proc. Roy. Soc.* B, **101**, 303–15.

(3) MARSHALL and CROSLAND (1918). *J. Min. Agric.* **24**, 1357–64.

(*Received July 17th*, 1928.)

CAMBRIDGE: PRINTED BY
W. LEWIS, M.A.
AT THE UNIVERSITY PRESS